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PLASTIC BIODEGRADATION THROUGH INSECTS AND THEIR SYMBIONTS MICROBES: A REVIEW

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ABSTRACT

Plastic waste has recently been identified as one of the most serious environmental issues, affecting all life forms, natural habitats, and the economy, and is one of the most serious global environmental problems, second only to climate change. Seeking alternative environmentally sustainable options, such as biodegradation instead of conventional disposal, is critical in the face of this challenge. However, there is currently a lack of information about the mechanisms and efficacy of plastic biodegradation. From this perspective, this study aims to illustrate the negative environmental impacts of the plastic waste. It also addresses the role of insects and gut microbiota in the degradation of plastics, emphasizing the important role they will play in the future.

Keywords: Biodegradation, plastic pollution, plastic eating insects, gut microbiota.

INTRODUCTION

Commercial plastic production, which started during the 1950s, has grown at an incredible rate. Plastics were produced in an estimated 6.3 billion tonnes from 1950 to 2018 (Alabi et al., 2019). Plastics production is expected to double in the next 20 years at the current pace of growth (Lebreton and Andrady, 2019). Plastic waste pollution is now universally acknowledged as a significant environmental burden. A recent study estimates that up to 6,300 million metric tonnes of plastic waste have been produced to date (Geyer et al., 2017). However, less than half of the produced plastic waste was either disposed of in landfills or recycled. A large portion of the remaining plastic waste litters continents, oceans, and every corner of our world, making it a "Plastic World" (Rochman et al., 2013).

The indiscriminate dumping of plastics on land and open-air burning will result in hazardous chemicals being released into the air, impacting all life forms, natural habitats, and public health risks (Alabi et al., 2019). Seeking environmentally sustainable options for its degradation, such as biodegradation instead of conventional disposal, is critical in light of this challenge (Ali et al., 2021). Plastic biodegradation is an important element in reducing the effects of plastic pollution (Wierckx et al., 2018). However, there is currently a lack of information about the mechanisms and efficacy of plastic biodegradation. The current review also addresses the concept of invertebrates, such as insects, in the degradation of plastics, emphasizing the critical role that they may play in the future.

Status of Plastic

Over the last few decades, global plastic production has increased, reached 359 million tonnes in 2018 (Lebreton and Andrady, 2019). Plastics have become one of the most commonly used substances on the planet since their consumption has increased rapidly. Plastic is widely used in the packaging of food, cosmetics, chemicals, pharmaceuticals, and detergents. With an annual global production of around 140 million Mg (tonnes), polyethylene (PE) is the most commonly used synthetic polymer (Sivan, 2011). The annual production of plastics reaches 180 million Mg (tonnes), with supply and demand increasing year after year. Plastic pollution is increasingly growing across the world as the number of plastic consumption rises. Up to 26 billion tonnes of plastic waste are expected to be produced by 2050, with more than half of that entering landfills and then entering ecospheres such as oceans and wetlands, creating major environmental pollution (Lönnstedt and Eklöv, 2016).

Plastic Waste Disposal and their Effects

Plastic waste is becoming more widely recognized (Jambeck et al., 2015), and it is becoming the most serious environmental problem of our time, next to climate change. Plastic wastes in landfills take up a lot of space. The 10,000 tonnes of plastic waste dumped in 0.067 hm^2 of land in landfills, releasing large amounts of chemicals in the process (Lithner et al., 2011). These harmful chemicals can leach into the soil and affect soil quality and groundwater (Crompton, 2007). PE waste buried in soil can disturb drainage pattern, disturb soil fauna, and lower soil quality, resulting in lower agricultural yields.

Plastic pollution enters the ocean at a rate of 0.48-1.27 million tonnes per year, Furthermore, the amount of plastic entering the ocean is at an incredible pace, with a doubling period of around 10 years (Crompton, 2007). Plastic particles contaminate the marine ecosystem and food system, particularly foods intended for human consumption (Lusher et al., 2017). Certain carcinogenic chemicals, including polycyclic aromatic hydrocarbons (PAHs), dioxins, nitro- PAHs, and others, can be emitted as airborne pollutants during the incineration of plastic wastes containing PS, PE, PVC, and PET (Al-Salem et al., 2009).

Harmful contaminants eluted from plastic waste or in the form of small or microplastic particles are more likely to enter food chains (Browne et al., 2008), and affect salt marsh grasses, mussels, and corals that are important ecological species (Uhrin and Schellinger, 2011). Plastics-related chemicals, as well as small and microplastic debris, could build up in the bodies of humans and mussels, causing harm to the cells and other body tissues (Pauly et al., 1998).

Methods of Plastics Degradation

Natural Plastic degradation is very sluggish, resulting in an accumulation of plastic waste that poses a serious environmental threat. Plastic degradation is affected by various type of factors, including age, weathering, polymer type, temperature, pH, and irradiation (Akbay and Özdemir, 2016). Plastic treatment consists of 77% reclamation, 13% incineration, and 10% mechanical and chemical recovery due to a lack of adequate degradation methods. Reclamation pollutes the soil and groundwater, as polyethylene waste is burned directly vapors are released that contain a variety of toxic carcinogens such as ketones and acrolein, as well as greenhouse gases such as methane, both of which pose significant health and environmental risks (Briassoulis, 2006).

Even though mechanical recycling has been the main recycling process for reusing thermoplastic wastes, after several manufacturing cycles, the characteristics of most recycled products have been negatively affected, and the resulting market appeal is minimal. Chemical recycling, as an option, will recycle monomers and other substances from 61 different plastic wastes, but its performance is dependent upon the cost of practices and the effectiveness of catalytic agents (Rahimi and García, 2017).

Plastic biodegradation by fungal and bacterial strains has been highlighted as a potential solution for removing plastic waste without producing secondary pollution (Lee et al., 2020), but they have some limitations they are slow in the process, and they required optimum conditions for biodegradation. Plastic waste biodegradation by the arthropods is an emerging solution, there are different plastic-eating worms are identified which can digest the plastic and convert it into non-hazardous compound (Bombelli et al., 2017). Seven types of plastics are degraded from the insects till now are (Polyethylene, polystyrene polyvinyl chloride, polypropylene, polyphenylene sulfide, ethylene-vinyl acetate, and extruded polystyrene). The mode of degradation of plastics in insects is still in progress but there are some assumptions that there is the role of enzymes and gut microbiota on insects.

Insects Identified as Plastics Eating Insects

i. Lepidoptera

It is an order of insects that includes butterflies and moths. In this order, Pyralidae family, some species are identified as plastic feeding insects are Indian meal moth (*Plodia interpunctella*), the lesser wax moth (*Achroia grisella*), the greater wax moth (*Galleria mellonella*), and Rice meal worm (*Corcyra cephalonica*).

ii. Waxworm

G. mellonella larval stage can chew and consume PE films because they can feed on and digest beeswax (Khyade, 2018; Yang et al., 2014). Since beeswax and PE have structural similarities, *G. mellonella* biochemical machinery for beeswax metabolism may be used for PE metabolism. Under in situ and in vitro conditions, the function of *G. mellonella* enzymes and intestinal microbiota in PE degradation is still unknown. It's important to find out how *G. mellonella* enzymes and microbiota contribute to PE degradation (Kong et al., 2019). *G. mellonella* larvae have a remarkable capacity to use pre-existing metabolic mechanisms to get energy from PE as a sole source of food (LeMoine et al., 2020). The worms were able to soften and metabolize thin-film PE shopping bags into ethylene glycol (Bombelli et al., 2017). Salivary glands can help in polyethylene degradation by forming pitting and degradation intermediates containing carbonyl groups (Peydaei et al., 2020). The function of putative lipid oxidative enzymes is significantly greater in larvae that fed PE, according to LeMoine et al., (2020).

A commercial PE shopping bag will lose 92mg of weight in 12 hours after being infected with 100 waxworms (Weber et al., 2017). The waxworm gut microbial symbionts also helped to degrade PE. Intestinal microbial symbionts have long been known to play a role in insect digestion, PE depolymerization has occurred in the waxworm gut (Yang et al., 2014; Engel and Moran, 2013). The *G. mellonella* had its guts examined for the biodegradation of PE by Enterobacter sp. D1 (Ren et al., 2019). The *G. mellonella* gut contents yielded PEDX3, a PE-degrading fungus *Aspergillus flavus*. Microplastic particles can be degraded by *A. flavus* strain PEDX3, and the two PE-degrading enzymes suggest that PE MPP remediation is a viable option (Zhang et al., 2020).

iii. Lesser Wax Worm

A. grisella can eat silo bags, which are made up of three layers of polyethylene and one anti-UV layer (Chalup et al., 2018). Lesser waxworms feeding PE, WC, or PE-WC completed all stages of the life cycle. New carbonyl and alcoholic groups appear in the frass of lesser waxworm-fed PE samples, as well as a rise in unsaturated hydrocarbon, indicate the development of biodegraded intermediates (Kundungal et al., 2019).

iv. Indian Meal Moth

P. interpunctella larvae can cause damage to polyethylene (PE) packing films by chewing and consuming them (Bowditch, 1997). *P. Interpunctella* contains gut bacteria that degrade the synthetic polymers (Mereghetti et al., 2017). *Enterobacter asburiae YT1* and *Bacillus sp. YP1* was isolated from the guts of *P. interpunctella* larvae in another study (Yang et al., 2014). After 28 days of incubation, they reduced the hydrophobicity of the PE film and caused surface disruption. *E. tabaci strain and B. subtilis subsp. Spizizenii strain* was isolated from the midgut larvae, and they have a role in degradation (Mahmoud et al., 2020).

Table 1: Plastic types degraded by Insects and their Symbiont microbes.

Plastic material	Insect Scientific name	Symbiont Microbes	Reference
Polyethylene	*G. mellonela*	*Enterobacter asburiae* YT1 *Bacillus sp*. YP1	(Yang et al., 2014)
		Enterobacter sp. D1	(Ren et al., 2019)
		Aspergillus flavus	(Zhang et al., 2019)
	A. grisella	-	(Kundungal et al., 2019)
	P. interpunctella	*Bacillus sp. YP1* and *Enterobacter asburiae YT1*	(Yang et al., 2014)
		Enterobacter tabaci strain and *Bacillus subtilis subsp. Spizizenii* strain	(Mahmoud et al., 2020)
	C. cephalonica	-	(Kesti and Thimmappa, 2019)
	T. molitor	*Citrobacter* sp. and *Kosakonia* sp.	(Brandon et al., 2018)
	Z. atratus	*Pseudomonas aeruginosa*	(Lee et al., 2020)
Polystyrene	*T. molitor*	*Exiguobacterium* sp. YT2,	(Yang et al., 2015b)
		Klebsiella, *Pseudomonas* and *Serratia*.	(Urbanek et al., 2020)
	T. obscurus	-	(Peng et al., 2020)
	Z. atratus	*P. aeruginosa*	(Lee et al., 2020)
	T. castanium *Uloma spp*	*Acinetobacter sp*. AnTc-1 -	(Wang et al., 2020) (Kundungal et al., 2021)
Polyphenylene sulphide	*Z. atratus*	*P. aeruginosa*	(Lee et al., 2020)
Ethylene-vinyl acetate	*T. confusum*	-	(Abdulhay, 2020)
Polyvinyl chloride (PVC)	*T. molitor*	-	(Peng et al., 2020)

v. ***Rice Meal Worm***

C. cephalonica larvae can degrade low-density polyethylene. It has been reported that, any gut microbes that may be responsible for degrading LDPE. It can be interpreted that enzyme for the decomposition of LDPE may be produced by the gut tract of these larvae (Kesti and Thimmappa, 2019).

Coleoptera

It is an order of insects that includes beetles and weevils**.** In this order, Tenebrionidae family, there are some species which are identified as plastic feeding insects are Meal worm (*Tenebrio molitor*), Super worm (*Zophobas atratus),* Confused flour beetle *(Tribolium confusum), Uloma spp,* and Red flour beetle *(Tribolium castaneum).*

Mealworm

T. molitor, is capable of depolymerizing and biodegrading polystyrene, polyethylene (Ghatge et al., 2020; Peng et al., 2020), polypropylene (Yang et al., 2021) and polyvinyl Chloride (PVC) (Peng et al., 2020). PS-degrading capacity was seen in a wider variety of mealworms from 12 different locations around the world, showing that PS degradation is common in mealworms (Yang et al., 2017). Mealworms were found to be capable of eating and quickly degrading up to 50 % of ingested PS in just 24 hours, according to changes in chemical composition, molecular weight, isotopic trace following tracks through the intestinal tract (Yang et al., 2015a).

In vitro, one strain of *Exiguobacterium sp.* YT2, isolated from the m *T. molitor* gut, was found to be capable of degrading 7.5 % of the weight of PS in less than 60 days (Yang et al., 2015b). Brandon et al., (2018) investigated how yellow mealworms degraded PE and plastic mixtures. Up to 49.0 ± 1.4 % of the ingested PE was metabolized to CO_2 after incubation with larvae. The molecular weights of egested polymer were reduced by 40.1 ± 8.5 % in mealworms feeding PE.

Kosakonia sp. and *Citrobacter sp*. were found to be abundant in the gut microbiome, according to a study using next-generation sequence analysis (Brandon et al., 2018). Mealworms can degrade polyethylene using enzymes such as esterase and cellulose, according to Przemieniecki et al., (2020). *T. molitor* can biodegrade PP through gut microbe-dependent depolymerization with a variety of microbiomes, according to Yang et al., (2021). *T. obscurus* was capable of consuming PS at rates that were much faster than *T. molitor*. TGA showed that T. *obscurus* larvae efficiently degraded PS based on the proportion of PS residue (Peng et al., 2019).

vi. Super Worm

Z. atratus larvae consume polystyrene, polyethylene, (Kim et al., 2020), and polyphenylene sulfide (PPS) foams (Li et al., 2020). The biodegradation of ingested Styrofoam was supported by microbial symbionts in the gut (Yang et al., 2015c; Yang et al., 2019), of plastic eating mealworms, more bacteria have been isolated, and their PS-degrading ability is still being evaluated (Xia et al., 2019). The PS, PE, and PPS can be degraded by *Pseudomonas aeruginosa* gut bacteria in *Z. atratus*. *P. aeruginosa* growth rates were not always proportional to biodegradation rates, and the structure and properties of intermediate molecules formed during plastic biodegradation may affect bacterial growth rates (Lee et al., 2020).

vii. Red Flour Beetle

Extruded polystyrene foam (EPS) was chewed and eaten by *T. castaneum* larvae (Fabreag and Familara, 2019). The gut microbiota of *T. castaneum* larvae fed plastic or bran revealed that *Acinetobacter sp*. was closely linked (Wang et al., 2020)**.** PS biodegradation can be mediated by a newly isolated Acinetobacter sp. AnTc-1 from a *T. castaneum* larva, and beetles (*R. dominica*, *T. variable*, and *T. mauretanicus*, with others in the Order Coleoptera) can eat, chew and penetrate a variety of plastic packing materials (Gerhardt and Lindgren, 1955; Cline, 1970).

viii. Confused Flour Beetle

Polyethylene foam, Polystyrene, and ethylene-vinyl acetate are degradable by *T. confusum*. During the study, an increase in the mass weight of the larvae was reported, indicating that plastic materials are not an effective source of energy for larvae other than survival. Larvae feeding PS, PE, and EVA lost 26.2, 31.4, and 45.8 % of their weight, respectively (Abdulhay, 2020).

P. davidis larvae can eat PS, and in 14 days, feed 34.27 ± 4.04 mg of Styrofoam (PS foam) per larva, surviving solely on Styrofoam. The oxidation of the swallowed Styrofoam was verified using Fourier-transform infrared spectroscopy (FTIR). *Serratia sp*. were developed on the PS film, which was isolated from the gut (Woo et al., 2020).

ix. ***Uloma spp*.**

Larvae feeding WC and PS completed all phases of the life cycle (larvae, pupae, beetles, egg) and PS degradation was favourable in the second generation. The study of egested frass using FTIR and HNMR revealed signs of depolymerization and oxidation, indicating that PS is effectively biodegraded in the gut tract (Kundungal et al., 2021).

CONCLUSION

The elimination of plastic pollution by developing new remediation methods could be helpful. Recent approaches on plastic degradation by insect groups have been indicating the presence of potential microbes. The biodegradation of plastics needs to explore extensively especially the identification of symbiotic microbiota of insects associated with plastic degradation. The gut microorganisms and digestive enzymes present in the whole digestive system of the insects play an important role in the overall physiological process of insects. However, molecular investigations on the entire physiological process of plastic degradation in the insect's gut need to be studied in detail and put an end to the plastic pollution concerns.

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