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Review Paper

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The Role of Insects and Microorganisms in Plastic Biodegradation: A Comprehensive Review

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Abstract— Plastic has been considered as a major environment polluting material for decades. Its physical, chemical and mechanical properties such as high tensile strength, elongation properties, high molecular weight, inertness and hydrophobic nature make it non-biodegradable. In spite of the fact that both environmental and microbial degradation of plastic have been studied in detail, most of the microorganisms reported so far are limited in their functions. However, the recent approaches in plastic degradation by use of insect caterpillars and their gut microbiota have shown interesting results. *Plodia interpunctella* (Indian meal worms), *Tenebrio molitor* (Yellow meal worms) and *Galleria mellonella* (Greater wax worms) are the insects reported till now in plastic degradation. In this comprehensive review, we have briefly focused on the general introduction and classification of plastics and properties which make plastic persistent in the nature. We also have glanced over certain Plastic biodegradation methods reported till today.

Keywords*— Plastic, Biodegradation, Insects, Persistent, Microbiota.*

I. INTRODUCTION

In the today's world, plastic is the most vital synthetic product which is being manufactured enormously and used for many purposes. The word 'plastic' is derived from the Greek word "*plastikos*" which means it can be molded into many shapes [1]. Plasticity during manufacture, which allows it to be cast, pressed, or extruded into a variety of shapes such as films, fibres, plates, tubes, bottles, boxes, and much more. Plastics are mainly derived from petrochemicals and are composed of long chain hydrocarbon polymers with high molecular weights [2]. During the last five to six decades plastics have been used in various applications and have been replaced with leather materials, wood, traditional metals and many more. The most preferred property of plastic is its durability which also exerts the major environmental problem of degradation. Practically, recycling of plastics has failed to provide a safe solution for disposal of plastic waste. United States of America alone produce 1 trillion plastic bags annually among which, only 5% is being recycled [3]. Basically, plastics are classified based on their thermal and designing properties. Based on thermal properties, plastics are categorized as *thermoplastics and thermosetting polymers*. Thermoplastics can be molded into any shape upon heating and these include Polyethylene (PE), Polystyrene (PS), Polypropylene (PP), Polyvinyl chloride (PVC), etc. with the molecular weight ranging from 20,000 to 500,000 amu. Thermosetting polymers once set into a definite shape cannot be molded again. These polymers cannot be recycled as their change is irreversible. Polyurethanes, Phenol-formaldehyde, etc are some of the examples of thermosetting polymers [4]. Designing properties of plastics are based upon their relevance of manufacturing processes, which include electrical conductivity, tensile strength, thermal stability, degradability and durability [4].

Biodegradation of plastic:

Biodegradation is defined as the degradation and assimilation of polymeric compounds by living organisms and formation of products such as CO_2, H_20, CH_4 and biomass [6]. In microbial biodegradation of plastics, the bacterial degradation of hydrocarbons is probably the first reported accounts [7] [8]. Biodegradation of plastics such as polyesters, polyhydroxybutyrates (PHB), polylactic acid (PLA), polyvinyl alcohol (PVA), nylon and Polyethylene (PE) has also been reported [2]. Zheng *et al*. provided a review on thermoset and thermo plastics [10]. Biodegradation of plastics involve both aerobic and anaerobic processes. In aerobic biodegradation, carbon-dioxide and water are formed as the end products, while in anaerobic process carbon-dioxide, water and methane are produced [11].

Environmental degradation of plastic:

Environmental degradation includes thermo- and photo-oxidation followed by biological activity (microorganisms). Various products such as alkanes, alkenes, ketones, aldehydes, carboxylic acids, alcohols, lactones and esters are formed when plastic is subjected to thermo- and photo-oxidation process. When plastic merges with the additives, auto-oxidation is enhanced and molecular weight of the polymer is reduced which makes the microorganisms to degrade the low molecular weight polymer [13].

Plastic Recycling Symbol	Plastic Name	Where to Find This Plastic in Your Home	This Plastic is Valued For
1 PETE	Polyethylene Terephthalate	water and soda bottles	clarity strength impermeability to gas and moisture
2 HDPE	High Density Polyethylene	milk jugs, grocery bags and toiletry bottles	stiffness strength resistance to moisture permeability to gas
3 V	Polyvinyl Chloride	water pipes, blister packaging for non-food items	strength ease of blending with other materials versatility
4 LDPE	Low-density Polyethylene	food bags, squeezable bottles, cling films, disposable cups	flexibility ease of processing ease of sealing barrier to moisture
5 PP	Polypropylene	microwaveable containers, yogurt cups, disposable plates / cups	strength resistance to heat, chemicals, oils and moisture
6 PS	Polystyrene	disposable plates, cups, cutlery, containers and packing peanuts	clarity versatility molding ease
7 OTHER	Other (often Polycarbonate or ABS)	beverage bottles, CD's, lenses for glasses, riot shields	properties dependent upon the mixture of polymers may contain BPA

Figure 1: Commonly used plastics and their applications [5]

Microbial degradation of plastic:

The curiosities on microbial degradation of plastics emerged when paraffin degradation by several microorganisms was reported [14]. Later on various microorganisms isolated from soil, water and dumping sites were reported [15]. Microbial degradation of plastics is caused mainly by enzymatic activities where the long chain polymer is cleaved into oligomers and monomers and then further metabolized by microbial cells. It may be aerobic or anaerobic metabolism. In aerobic, the end products after degradation are carbon dioxide and water [15], where as in anaerobic metabolism, carbon dioxide, water and methane are the end products [16]. Several microorganisms like bacteria, fungi and microalgae have been reported in plastic degradation.

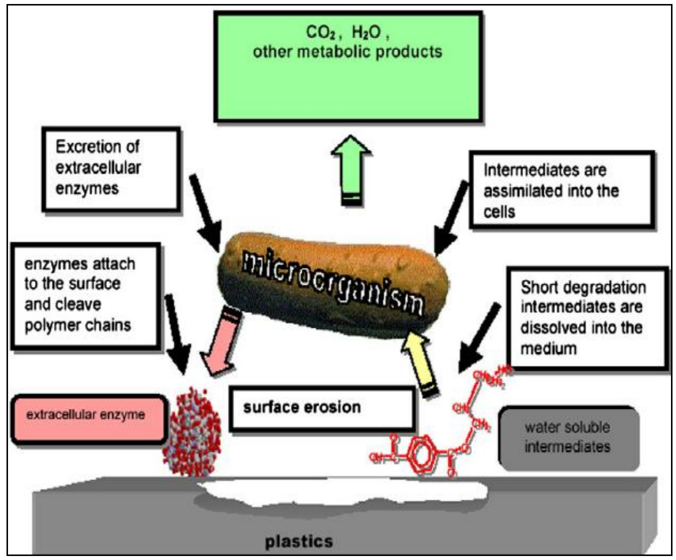

Figure 2: General mechanism of plastic biodegradation [12]

Properties of plastic which makes it non-biodegradable (Persistent):

High molecular weight, hydrophobicity and complex three-dimensional structure makes the plastic recalcitrant for biodegradation. For enzymatic degradation process, melting temperature (Tm) plays a crucial role. Generally, enzymatic activity decreases with increasing time. Higher order structures such as crystalline nature and elasticity suppress the plastic degradation. Furthermore, the additives, stabilizers, physical form of polymer and molecular composition also have an influence on plastic degradation [17].

Mechanisms of plastic biodegradation:

Biodegradation processes of synthetic plastics have not been understood fully, details of some of them have been known. Biodegradation mechanisms of some of the versatile synthetic polymers such as Polyethylene (PE), Polystyrene (PS) and Polypropylene (PP) have been described below:

Polyethylene (PE):

PE is the most common synthetic polymer with $–CH_2-CH_2-$ repeating units as the backbone. The characteristics of PE which make it resistant to biodegradation are: 1) highly stable C-C and C-H covalent bonds, 2) high molecular weight of PE which resist them to penetrate the cell walls of microorganisms, 3) lack of chromophores which act as catalysts for interdependent photo and biodegradation, and 4) highly hydrophobic nature [18]. Several microorganisms, such as *Actinobacter*, *Streptomyces*, *Aspergillus*, *Penicillium*, and *Mucor* have been reported till now [4] [19] [20].

Polystyrene (PS)

Polystyrene is a synthetic hydrophobic polymer with high molecular weight. Due to its hydrophobic nature and high molecular weight it is not readily biodegradable. Several strains of *Actinomycetes* have been reported in PS biodegradation, but the degree of degradation was very low [21]. Numerous species of fungi and bacteria have been reported in PS biodegradation, although the rate of biodegradation was very low, but with the addition of cellulose and minerals the degradation rate was increased [22] [23].

Polypropylene (PP)

Polypropylene belongs to thermoplastics category which is used in packaging materials, plastic molding, stationery, diapers, etc. In environmental degradation, exposure of PP to ultraviolet radiations and oxidation at high temperatures break down the polymer into simpler molecules and in microbial degradation, several species of fungi and bacteria such as *Aspergillus spp*., *Pseudomonos*, *E.coli*, and *Vibrio spp*. have been reported [3] [24].

Table 1: List of microorganisms involved in plastic biodegradation.

Sl. No.	Microorganisms	Type of plastic used	References
1.	*Bacillus sp.*	Polyurethane	[25]
2.	*Pseudomonas aeruginosa*	PVC powder	[26]
3.	*Rhodococcus Rhodocorrous* ATCC 29672 and *Nocardia steroids* GK911	Degradable polyethylene	[27]
4.	*Streptococcus sp., Staphylococcus sp., Micrococcus sp., Moraxella sp.*, and *Pseudomonas sp.*	Polyethylene bags and plastic cups	[28]
5.	*Pseudomonas sp*. (P1, P2, and P3)	Natural and synthetic polyethylene	[29]
6.	*Bacillus cereus, Bacillus megaterium, Bacillus subtilis,* and *Brevibacillus borstelensis*	LDPE and LLDPE	[30]
7.	*Aspergillus flavus* and *Mucor rouxii* NRRL 1835	Disposable plastic films	[31]
8.	*Aureobasidium pullulans, Rhodotorula aurantiaca,* and *Kluyveromyces spp.*	Plasticized PVC	[32]
9.	*Penicillium pinophilium* and *Aspergillus niger*	Low density polyethylene (LDPE) powder	[33]
10.	*Fusarium sp.* AF4	LDPE	[34]
11.	*Aspergillus spp.*	HDPE	[35]

Insects:

Being the most diversified organisms on earth, insects are known to exhibit a wide number of applications which are being explored by humans. Insects like Silkworm, Black soldier fly, *Galleria mellonella* (Greater wax moth), and many more agriculturally important ones are being highly used in biotechnological research. Among these, a recent approach on plastic degradation by insects has become a fascinating area in environmental plastic pollution issues. The gut microorganisms of *Plodia interpunctella*, also known as Indian meal worm were able to degrade polyethylene (PE) [36] [37]. Later, the similar study was carried out with *Tenebrio molitor* (Yellow meal worms) and reported that the meal worms could chew and eat Polystyrene (PS), commonly called as Styrofoam. Polystyrene digestion in yellow meal worms was studied by isotopic tests [38] [39]. Recently, it was also found that the caterpillars of *Galleria mellonella*, commonly known as Greater wax moth larvae could degrade Polyethylene (PE) at a higher rate compared to *Plodia interpunctella* and *Tenebrio molitor* [40].

Insects used in plastic degradation:

Plodia interpunctella, known as Indian meal worm has been considered as a major pest in agriculture and commonly called as stored grains pest. Indian meal moth larvae have been found to pierce into the plastic bags and damage the food grains. Indian meal worms were able to chew and eat Polyethylene (PE) when they were left in direct contact with PE [36]. *Enterobacter asburiae* YT1 and *Bacillus spp.* YP1 were the two prominent microorganisms found in the gut of *Plodia interpunctella* and responsible for PE degradation [36]. A complete genome of *Bacillus spp.* YP1 was sequenced and found relevant to PE biodegradation [37].

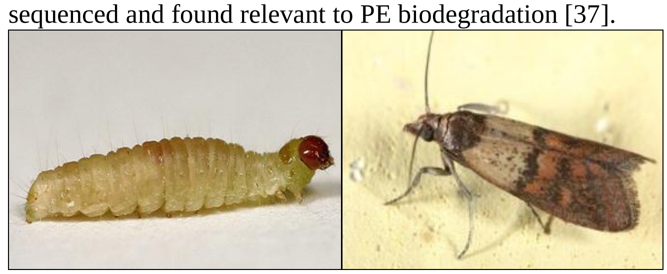

Figure 4: *Plodia interpunctella* larva and moth

Tenebrio molitor, also known as Darkling beetle, the larval form is called Yellow meal worm. Meal worms feed on stored food grains and are considered as pests. It was found that the Yellow meal worms could degrade Polystyrene [38] [39]. The larvae were fed with Styrofoam (a common PS product) as a sole diet and they survived as well as those fed with normal diet (bran). The degradation of PS was analyzed by using various analytical methods and isotopic tests. According to the study conducted by Yang *et al.*, in a 16 day test period, 47.7% of the PS carbon was converted into CO_2, indicating the degradation of PS [38]. *Exiguobacterium spp*. strain YT2 was found in the gut of yellow meal worm. When the bacterial strain was incubated with PS film, a biofilm was formed after 28 days associated with a decrease in PS surface hydrophobicity [39].

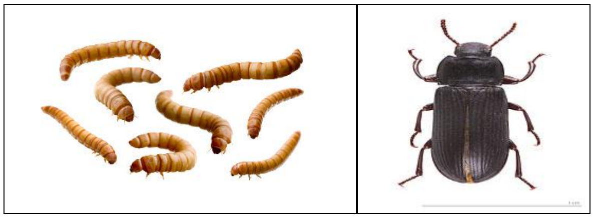

Figure 5: *Tenebrio molitor* larvae and adult

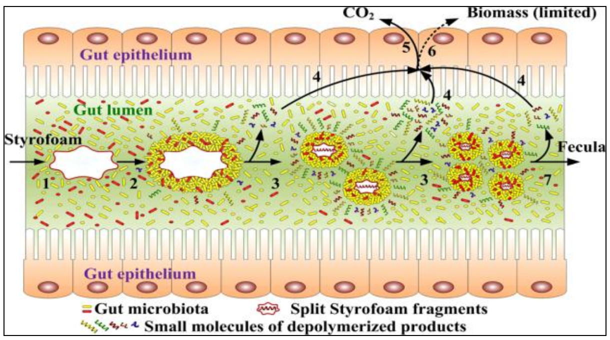

Figure 6: A proposed system for PS degradation in the gut of *Tenebrio molitor* larva. (Yang *et al.*) [39]

Galleria mellonella, also known as Greater wax moth is a serious pest in apiculture. Recently it was found that *Galleria mellonella* larvae could degrade polyethylene and convert it into ethylene glycol as an end product. The holes were formed when *Galleria mellonella* larvae were left in direct contact with PE. As reported, in 12 hours of time 100 larvae caused a mass loss of 92mg to the PE. After performing Atomic force microscopy, FTIR and TGA it was found that there was an obvious change in the topography of PE surface, formation of ethylene glycol and carbonyl bond on the homogenate treated area and 13% of mass loss of PE over 14 hours of treatment respectively, indicating the sign of PE degradation [40].

Galleria mellonella being a serious pest of beehive naturally feed on beeswax. The adults lay their eggs in the beehive where the larvae grow eating beeswax. Chemically, beeswax is composed of lipid compounds, including alkanes, alkenes, esters and fatty acids [41]. Further investigations on the role of gut microorganisms and enzymes responsible for PE degradation need to be reported.

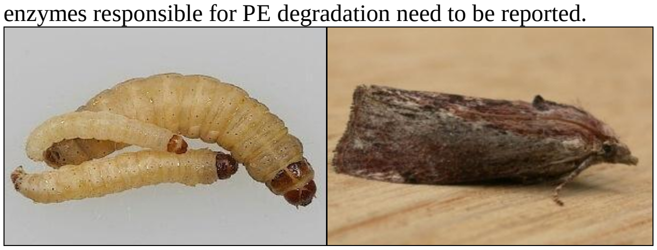

Figure 7: *Galleria mellonella* larvae and moth

II. CONCLUSION

The elimination of plastic pollution by developing new remediation methods could be helpful. Thermo- and photo-based pretreatments followed by microbial degradation reported till now have shown a very low efficiency in plastic degradation. Even though several microorganisms isolated from different areas have been reported till now practically, none of the organisms have found efficient. Recent approaches on plastic degradation by insects and their gut microorganisms have shown very interesting results. The gut microorganisms and digestive enzymes play an important role in 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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