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Review

Degradation of Plastic Materials Using Microorganisms: A Review

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ABSTRACT

Plastics are polymers of higher molecular mass of synthetic or semi-synthetic organic solids used as inputs for industries. Over the last few years, the need for biodegradable plastics has led to extended significance due to the extreme use of plastics and increasing pressure being positioned on to be had capacities for plastic waste disposal. Lack of degradability and the closing of landfill sites as well as growing water and land pollutant problems have caused the situation about plastics. Plastics are causing great difficulty in environmental problems and consequently, this desires manufacturers to synthesize materials that do not have an impact on the environment. The use of microorganisms in the surrounding to metabolize the molecular shape of plastic materials to produce an inert humus-like material and this is much less dangerous to the surroundings, furthermore, expertise their interaction and the biochemical adjustments they undergo are tremendously essential. In addition, the use of bio-active compounds coated with swelling materials ensures that once it is far mixed, with heat and moisture, they make bigger the plastics molecular structure and permit the bio-lively compounds to metabolize and neutralize the plastic. Thus, this overview article is revised to inspire and make an impact on the importance of microorganisms on biodegradation plastic substances.

Keywords
Biodegradation; Microorganisms; Plastics; Pollution; Hazard.

INTRODUCTION

Plastic is a matter that is hard to destroy and degrade once manufactured that goes in contradiction to natures rule; consequently, it creates a catastrophe for the complete world. Plastic is a broad term given to the various types of natural polymers having high molecular weight and is generally derived from distinct petrochemical merchandise. Most plastics are non-biodegradable and few are degradable but at a completely sluggish fee. Thus, plastics continue to be in nature with none deformation for a totally long time on account that they are obviously inert and proof against microbial degradation.[1,2]

Plastics are ubiquitous in modern life and their early uses date again to 1600 B.C. The exploitation of plastics started in 1839 with the discovery of vulcanized rubber and polystyrene.[3,4] The international utility of plastics is expanding at a rate of 12% per annum and approximately 140 million tons of synthetic polymers are produced globally each year. Plastics commodities are utilized in fishing nets, packaging, food industry, and the agricultural sector.[5,6]

After their usage, these packing materials are discarded in landfill principal pollutants and considered as the most important environmental problem since they are non-biodegradable under natural environmental circumstances. The accumulation of these plastic wastes created a serious threat to the environment and wildlife. The dispersal of household and industrial wastes pollutes the soil and these are mainly due to human activities.[7,8]

Animals are dying of waste plastics both by being stuck inside the waste plastic traps or by swallowing the waste plastic debris to exert catastrophic outcomes on the surroundings. Some of the plastic products motive, human health problems when you consider that they mimic the human hormone. Among these, vinyl chloride is classified as carcinogenic to humans and mammary carcinogen in animals by the International Agency for the Research on Cancer (IARC). Polyvinylchloride (PVC) is used in numerous purchaser merchandise, along with adhesives, detergents, lubricating oils, solvents, automotive plastics, plastic apparel, personal care products in addition to toys and constructing materials.[9,10]

Consequently, there was a need to design biodegradable polymers that degrade easily upon disposal through the action of living microbes. These polymeric materials are capacity resources of carbon and provide strength for microorganisms like bacteria and fungi which can be heterotrophic in nature. Recently, numerous microorganisms were reported to produce degrading enzymes that yield byproducts that are non-poisonous to nature in addition to residing organisms after decomposition. It is taken into consideration to be the safest technique of breakdown with much less poisonous aspect products and having the potentials of biogeochemical cycling of the substrate.[11,12] Hence, this review article was prepared to enlighten the role of microorganisms for biodegradation of plastic and to illustrate the burden on the natural, especially to the aquatic environment and the soil.

PLASTICS TYPE AND HAZARD OF PLASTICS

Plastics are of numerous types and categorized based on their properties and chemical shape.[13,14]

Thermal Properties

On the basis of plastic's thermal properties, plastics are further sub-divided into thermoplastics and thermosetting polymers.[13-15]

Thermoplastics: Thermoplastics are polymers that don't change with their chemical composition whilst upon heating and might undergo molding numerous times. Polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC) and polytetrafluoroethylene (PTFE) are many of the most not unusual varieties of polymers. They also are known as not unusual plastics, variety from 20,000 to 500,000 atomic mass units (AMU) in molecular weight and have extraordinary numbers of repeating gadgets derived from an easy monomer unit.[3,16]

Thermosetting polymers: Thermosetting polymers, which include phenol-formaldehyde, polyurethanes, are different types of plastics that remain solid upon heating since they cannot be softened and changed. The chemical change is irreversible and consequently, these plastics are not recyclable due to the fact they have got a noticeably pass-linked structure, whereas thermoplastics are linear. The different way of plastic classification is based upon their relevance to the manufacturing technique and designing. It is classified in special parameters like electrical conductivity, durability, tensile strength, degradability, and thermal stability. The chemical properties of plastics are vital criteria for differentiating them into degradable and non-degradable polymers.[3,14,16]

Non-biodegradable plastics are also referred to as synthetic plastics and are derived from petrochemical products. These have an unusual repeat of small monomeric units with very excessive molecular weight. On the other hand, the degradable plastics are fabricated from starch and do not have very high molecular weight. These are generally getting broken down upon the interaction with ultraviolet (UV), water, enzymes and sluggish changes in pH. Bio pool is a highly-priced biodegradable plastic, comprised of polyhydroxy butyrate and available in the market.[8,17]

Hazards of Plastics

Chlorinated plastic can release harmful toxins into the soil, which may affect the groundwater environment. Methane gas, a highly powerful greenhouse gas produced for the duration of the degradation system appreciably causes international warming. In the ocean, plastic pollutants can kill marine mammals without delay through tangle in gadgets, consisting of fishing equipment, but it could also kill *via* ingestion, through being mistaken for meals.[18,19]

Studies have determined that each type of species, inclusive of zooplankton, cetaceans, seabirds, and marine turtles, easily ingest plastic and trash items which includes cigarette lighters, plastic bags, and bottle caps. Sunlight and seawater embrittle plastic and the eventual breakdown of large items makes it a polyethylene, a shape of plastic including shopping luggage, disposable bottles, and glasses, chewing gums, and toys, which is assumed to be carcinogenic. Phthalates, found in emulsions, inks, footwear, and toys among other merchandise, are related to hormonal disturbances, developmental troubles, most cancers, decreased sperm count and infertility and weakened immunity.[2,11]

Degradation of PVC for the duration of processing is dangerous for the surroundings and human animals (Murphy, 2001). Several polybrominated flame retardants are persistent, bioaccumulating and poisonous in nature and are also listed inside the Stockholm Convention on Persistent Organic Pollutants (POPs).[3,20] Among the phthalate plasticizers the most hazardous ones i.e. Benzyl butyl phthalate (BBP), di(2-Ethylhexyl)phthalate. DEHP and DBP, are categorized as poisonous and impair reproduction. BBP is also very poisonous to aquatic organisms with long-lasting outcomes. In addition, those phthalates, as well as DEP (diethyl phthalate) and DCHP (di-cyclohexyl phthalate), are being evaluated for the endocrine-disrupting properties (Figure 1).[5,21]

Figure 1. *A Grey Seal Inside a Sealed Shelter at Texel, Netherlands. The Seal Became Entangled in a Nylon Thread that had cut into the Flesh and Damaged the Spine.*[22]

BIODEGRADATION OF PLASTICS

Plastic biodegradation is a process of changing properties such as tensile strength, color, chemical structure, shape, and the molecular weight of plastic polymers through microbial degradation. This process involves enzymatic and non-enzymatic hydrolysis of microorganisms, especially bacteria, and fungi.[22,23]

Biodegradability depends both on the origin of the polymer, and on its chemical structure and the environmental degrading conditions. The factors that have an effect on the mechanical nature of biodegradable substances are their chemical composition, production, garage and processing characters, their aging and the application conditions. Plastics are generally biodegraded aerobically in nature, anaerobically in sediments and landfills and partially aerobically in compost and soil.[24]

Aerobic Biodegradation

Aerobic biodegradation is known as aerobic respiration and is an important part of the natural reduction of contaminants in many hazardous waste sites. Aerobic microbes use oxygen as an electron acceptor and break down organic chemicals into smaller organic compounds with CO_2 and water by-products.[3,25]

Anaerobic Biodegradation

Anaerobic biodegradation is the decomposition of organic contaminants by using microorganisms with the absence of oxygen and is likewise a crucial component of the natural reduction of contaminants at dangerous waste sites. Some anaerobic bacteria use nitrate, sulfate, iron, manganese and carbon dioxide as their electron acceptors, to interrupt down organic chemicals into smaller compounds, C plastic$\rightarrow CH_4+CO_2+H_2O+$C residual+Biomass.[24]

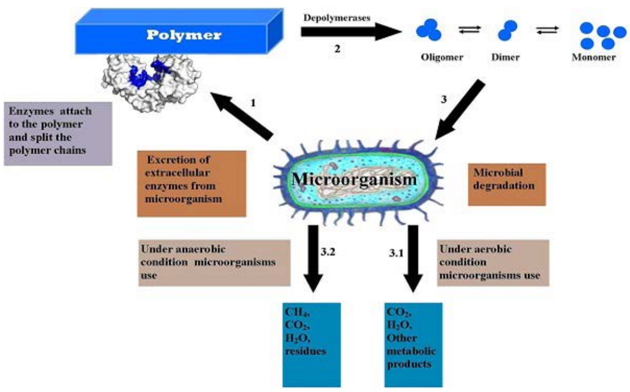
Mechanism of Biodegradation

Microorganisms are not able to move the polymers without delay through their outer cellular membranes into the cells in which most of the biochemical processes take place since polymer molecules are long and no longer water-soluble. In order to apply such substances as a carbon and strength supply, microbes evolved a method wherein they excrete extracellular enzymes that depolymerize the polymers outdoor the cells. Anaerobic and aerobic biodegradation mechanism pathways are given in Figure 2. Biodegradation of polymers entails the following steps:

1. Attachment of the microorganism to the surface of the polymer.
2. Growth of the microorganism, using the polymer as a carbon source.
3. Ultimate degradation of the polymer.[15,23]

Microorganisms are able to attach to a polymer's surface, as long as the latter is hydrophilic. Once the organism is connected to the surface, it could grow the usage of the polymer as its carbon supply. In the number one degradation level, the extracellular enzymes secreted *via* the organism inflicting the primary chain to cleave, leading to the formation of low-molecular-weight fragments, like oligomers, dimers or monomers. These low molecular weight compounds are further utilized by the microbes as carbon and electricity assets. Small oligomers might also diffuse into the organism and get assimilated in its inner environment.[26,27]

Figure 2. *General Mechanism of Plastic Biodegradation Under Aerobic and Anaerobic Conditions.*[23]



Bacterial and Fungi Species Involved in Biodegradation

There are many microorganisms (especially of bacterial and fungal origin) that have a mechanism to degrade large and complicated hydrocarbons into simpler biomolecules. They are in particular Gram-positive and Gram-negative as well as a few species of fungal origin like *Aspergillus*. Other species of microbes like *Streptococcus, Staphylococcus, Micrococcus* (*Gram-negative*), *Moraxella* and *Pseudomonas* (*Gram-positive*) and species of fungi (*Aspergillus glaucus* and *Aspergillus niger*) are worried in biodegradation system. In addition, *Bacillus megaterium, Ralstonia eutropha, Azotobacter, Halomonas* species are involved in the breakdown method (Table 1).[28,29]

Factor Affecting Biodegradation of Plastics

Biodegradation is governed by means of different factors that consist of polymer characteristics, type of organism and nature of pretreatment. The polymer characteristics along with its mobility, crystallinity, molecular weight, the sort of purposeful business and substituents present in its structure and plasticizers or components delivered to the polymer all play a vital role in its degradation.[23,34]

Chemical and physical homes of plastics play a crucial role in their biodegradation. Sidechain owning polymers are tough to degrade while in comparison to polymers without side chains. It needs to also be saved in thoughts that polymers with excessive molecular weight are difficult to degrade. The other factors worried within the biodegradation of polymers are their morphology, melting temperature and degree of crystallinity. If the polymer is amorphous, then it will be degraded without difficulty as compared to crystalline polymer. Polymers with excessive melting temperatures are hard to biodegrade. Thus, if biodegradation of plastics is to be executed at the industrial level, all these factors must be kept in mind.[28]

Table 1. *List of Some Microorganisms*

Sources	Enzyme	Microorganisms	Plastics	Reference
Bacteria	Lipase	*Clostridium botulinum*	PCL	2,30
	Unidentified	*Firmicutes (Phylum)*	PHB, PCL, and PBS	2
	Serine hydrolase	*Pseudomonas stutzeri*	PEA, PBS, and PCL	5
	Unidentified	*Brevibacillus borstelensis*	PHA	31
	Unidentified	*Pseudomonas fluorescens* *Pseudomonas putida* *Ochrobactrum (Genus)*	PET	32,33
	Unknown	*Streptomyces (Genus)*	PHB, PVC	2
	Manganese peroxidase	*Amycolatopsis species*	PLA, PE	5
	Glycosidase	*Aspergillus flavus*	PCL	2
Fungi	Unidentified	*Penicillium funiculosum*	PHB	
	Catalase, protease	*Aspergillus niger*	PCL	
	Lipase	*Rhizopus arrizus*	PEA, PBS, and PCL	
		Rhizopus delemar	PCL	
	Cutinase	*Fusarium (Genus)*	PCL	5

PCL-Polycaprolactone, PHB- Polyhydroxybutyrate, PLA- Polylactic Acid, PE-Polyethylene, PVC- Polyvinyl chloride, PET- polyethylene terephthalate, PEA-Polyesteracetals, PBS-Polybutylene succinate, PHA-Polyhydroxyalkanoates

The biodegradability of a polymer is essentially determined by the following 8 physical and chemical characteristics:

1. The availability of functional groups that increase hydropho bicity (hydrophilic degradation is faster than hydrophobic).
2. The molecular weight and density of the polymer (lower degrades faster than higher).
3. The morphology of polymer plastic that depends on the amount of crystalline and amorphous regions (amorphous degrades faster than crystalline).
4. Structural complexity, such as linearity or the presence of branching in the polymer.
5. Presence of easily breakable bonds such as ester or amide bonds. Chain coupling (ester>ether>amide>urethane).
6. Molecular composition (blend).
7. The nature and physical form of the polymer (e.g., films, pellets, powder or fibers).
8. Hardness (Tg) (soft polymers degrade faster than hard ones).[3,13,15]

BIODEGRADATION OF NATURAL PLASTICS

Bioplastics are a special type of biomaterial. They are polyesters produced by different microorganisms and cultured under different nutrient and environmental conditions. These polymers, usually lipid in nature, are accumulated as storage materials and allowing microbial survival under stress conditions. The number and size of the granules, the monomer composition, macromolecular structure, and physicochemical properties vary widely, depending on the producer organism.[5,35]

Biodegradation of Polyhydroxyalkanoates, PHB & PHBV

Microorganisms that produce and store PHA under nutrient-limited conditions may degrade and metabolize it when the limitation is removed. However, the ability to store PHA does not necessarily guarantee the ability to degrade it in the environment. Individual polymers are much too large to be transported directly across the bacterial cell wall. Therefore, bacteria must have evolved extracellular hydrolases capable of converting the polymers into corresponding hydroxyl acid monomers. The product of PHB hydrolysis is R-3-hydroxybutyric acid,[3,36] while extracellular degradation of PHBV yields both 3-hydroxybutyrate and 3-hydroxy valerate. In general, no harmful intermediates or by-products are generated during PHA degradation. In fact, 3-hydroxybutyrate is found in all higher animals as blood plasma. For this reason, PHAs have been considered for medical applications, including long-term controlled drug release, surgical pins, sutures, and bone and blood vessel replacement.[5,37,38]

BIODEGRADATION OF SYNTHETIC PLASTIC

The primary mechanism for the biodegradation of high-molecular-weight polymer is the oxidation or hydrolysis by an enzyme to create functional groups that improve the hydrophobicity. Physical properties such as crystallinity, orientation, and morphological properties such as surface area, affect the rate of degradation.[16,19,39]

Polyethylene (PE)

Polyethylene is a stable polymer that consists of long chains of ethylene monomers; it cannot be degraded easily by microorganisms. However, it has been reported that lower molecular weight PE oligomers (MW=600-800) can be partially degraded by Actinobacter species. upon dispersion, while high molecular weight PE could not be degraded. Biodegradation of polyethylene is known to occur by two mechanisms: hydro-biodegradation and oxo-biodegradation.[3,8,40]

UV light acts as an activator, used at the beginning of the degradation process for the activation of an inert material such as Polyethylene. Similarly, it was also treated by exposing it to UV light and also treated with nitric acid. This pretreated polymer was then exposed to microbial treatment using Fusarium species. Asymmetrical flow field-flow fractionation (AF4) is a fractionation method that is used for the characterization of nanoparticles, polymers, and proteins. The theory for AF4 was conceived in 1986 and was established in 1987. It is a separation technique based on the theory of field flow fractionation. AF4 is a mineral salt medium containing treated plastic as a sole source of carbon and energy. An increase in the growth of fungus and some structural changes as observed by Fourier-Transform Infrared Spectroscopy (FTIR) were observed in the case of treated PE, which indicated the breakdown of the polymer chain and the presence of oxidation products of polyethylene.[41,42]

Polypropylene (PP)

Polypropylene is a thermoplastic that is commonly used for plastic moldings, stationery, folders, packaging materials, plastic tubs, non-absorbable sutures, diapers, etc. It can be degraded by exposure to ultraviolet radiation from sunlight, and it can also be oxidized at high temperatures. The possibility of degrading PP with microorganisms has also been investigated. Studies reported on biodegradation of PP, many microbial communities such as certain fungal species like Aspergillus niger and bacteria such as Pseudomonas and Vibrio have been reported to biodegrade PP. A decrease in viscosity and the formation of new groups, namely carbonyl and carboxyl, were observed during the degradation process.[15,27,43]

Polyvinyl Chloride (PVC)

Polyvinyl chloride (PVC) is a strong plastic that resists abrasion and chemicals and has low moisture absorption. Mostly, PVC is used in buildings for pipes and fittings, electrical wire insulation, floor coverings, and synthetic leather products. It is also used to make shoe soles, rigid pipes, textiles and garden hoses. There are many studies about thermal and photodegradation of PVC but they are only a few reports available on biodegradation of PVC. PVC having a low molecular weight can be exposed to biodegradation by the use of white-rot fungi.[15,17,44]

Polystyrene (PS)

Polystyrene is a synthetic plastic used in the production of disposable cups, packaging materials, in laboratory ware, in certain electronic uses. PS is used for its lightweight, stiffness and excellent thermal insulation. When it is degraded by thermal or chemical means it releases products like; styrene, benzene, toluene and acrolein.[3,9,27]

CONCLUSION AND RECOMMENDATION

Plastics are very useful in our day-to-day life to meet our desired needs. Due to its good quality, its use is increasing day by day and its degradation is becoming a great threat. In the natural environment, different kinds of microorganisms play an important role in various steps involved in the degradation of plastics. Studying the synergism between those microorganisms will give an insight for future efforts toward the biodegradation of plastic materials. The plastic materials have high-molecular-weight and have hydrophobic surfaces, making them difficult for the microorganisms to form stable biofilms and degrade them into small molecular oligomers. Various plastic-degrading methods are available, but the cheapest, eco-friendly, acceptable method is degradation using microbes. The microbe releases the extracellular enzymes to degrade the plastic with the complex enzymatic reaction, but further investigation still needed to be carried out. Utilization of molecular techniques to detect specific groups of microorganisms involved in the degradation process will allow a better understanding of the organization of the microbial community involved in the attack of materials. The characterization of efficient plastic-degrading microbes at the molecular level is still not available, so research should be focused in the field of genomics and proteomics, which could speed up the degradation.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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