Chapter 1

Introduction, Past and Present Scenarios of Plastic Degradation

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Abstract

The fascinating properties of plastic make its use widely possible in every field for the ease of human life. On the other hand, these properties make plastic non-biodegradable in nature. Hence the increasing accumulation of plastic in the environment is the arising concern for environmentalists and human society. This growing concern has motivated researchers and technologists to promote research activity for finding new degradation methods for plastics, synthesis of new plastic with biodegradable nature or find alternatives to plastics. Considering these facts, this book chapter briefly discusses the management of post-consumer plastic products and all the possible methods for plastic degradation such as photo and thermo-oxidative, catalytic, mechano-chemical and chemical along with the factors affecting these degradation methods.

Keywords

Plastics, Degradation, Biodegradation, Thermo-Oxidative, Photo-Oxidative, Catalytic Degradation

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The resilience behavior of plastic against degradation and its indiscriminate use by humans leads to the accumulation of plastic in the environment, which arises as a serious concern for global ecology and biodiversity [1-2]. The word plastic is taken from the Greek word plastikos which means ability to deform into different shapes without breaking [3]. Plastics are synthetic, organic long chain, high molecular mass polymeric molecules usually synthesized from petrochemicals (oil, coal and natural gas) and often contain N, O, Si, Cl etc. [4-6]. Hence those polymers which have plasticity property (in a class of moldable solid polymers) are known as plastics [7].

Due to the ease of fabrication, low cost, flexibility, toughness, resistivity towards corrosion, microorganisms and water, good barrier properties, durability and high stability, plastics are used in various products in different fields with varying scale from paper tie up pin to spacecraft [4, 8-11]. Hence plastic materials are considered as a group of materials which is resistant to many environment influences. With these properties, synthetic plastics have prevailed/ substitute the traditional/ natural materials such as malleable metals, wood, glass, ceramic, leather, cotton etc. and became an unavoidable part of human lives. These features make plastic a very popular material, used massively in every field but on the other side these features make it an environmental threat [9, 12-19].

The proliferation of synthetic plastic in different fields is due to its multitude applications. The global production of plastic was 381 million tons in 2015 of which 42% (146 million tons) was used in packaging industry like pharmaceuticals to consumer items, grocery to vegetables products, cosmetic to chemicals and nearly 19% (65 million tons) in building and construction field like piping, vinyl siding etc. The commonly used plastics for packaging application are polyethylene (low density polyethylene (LDPE), high density polyethylene (HDPE), medium density polyethylene (MDPE), linear low density polyethylene (LLDPE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyurethane (PUR), poly (ethylene terephthalate) (PET), poly (butylene terephthalate) (PBT), nylons. The plastics used in packing have a very short lifetime than the other sectors [20- 22].

According to British plastic federation report (2009) nearly 25,000 companies in India are involved in plastic production and produced nearly 5.27 million tons of plastics (in 2009) of which packaging and agriculture sector consume maximum amount of plastic.

The plastic industry development rate in India is one of highest in the world, with the increasing plastic consumption rate of 16% per annum as compared with other countries such as 10% per annum in China and nearly 2.5 % per annum in United Kingdom (UK). According to the report of Statista Research Department (2016), the per capita consumption (in kilogram) of plastic materials in different region of the world is as follow: NAFTA i.e. North America Free Trade Agreement countries: Canada, the United States and Mexico (139 kg per capita), Western Europe (136 kg per capita), Japan (108 kg per capita), Central Europe and Commonwealth of Independent States (CIS) (48 kg per capita), Asia (excluding Japan) (36 kg per capita), Middle East and Africa (16 kg per capita), World total (45 kg per capita). Plastic consumption by an Indian in a year is 11 kg (global average is 28 kg per year) while an American can consumes nearly 109 kg per year [23,19,24]. As stated by central pollution control board in 2015, nearly 6.92% plastic waste of the total municipal solid waste was generated in India. Approximately 50% of plastic is produced for use and throw purpose but their accumulation in the environment is for several hundred years. The World Bank analysis reveals that the world generates maximum 242 million tons of plastic waste-nearly 12% of all municipal solid waste (MSW), in which 9% plastic waste has been recycled, nearly 12% incinerated and the remaining plastic waste (79%) dumped in the land or natural environment and nearly 8 million tons of plastic ends up in the ocean [25, 26]. Hence plastic waste reaches from the niche of the ocean to Mount Everest. Plastic waste in the oceans originates from both land bases (80%), marine bases (20%). The plastic debris ingestion by the animals leads to many problems such as persistence of plastic in the stomach, gastrointestinal blockage, decreased secretion of gastric enzymes, fertility problems [1]. Most of the rivers located in Asia are highly polluted and deliver 86% of plastic in the oceans. The Chinese river “Yangtze” contains maximum amount of plastic debris (1,469,481 tons) and is highly polluted in the world [20]. Eriksen et al. [27] estimated that there was approximately 269000 tons of plastic in the surface water across the world. The commonly found plastic waste is plastic bottles, bottles caps, food wrappers, straw and stirrer.

Plastic, the magical material has a flipside, it is not degrade naturally. Usually the commodity plastics (~99%) originates from petrochemicals (i.e. synthetic plastic) and is non- biodegradable in nature or degrades in a very slow rate [28]. The main obstacle for plastic degradation is the high molecular weight of the plastic. The microorganism cannot grasp the higher molecular weight compounds [29]. The continuous improvement in plastic properties with the help of additives such as plasticizers, stabilizers, cross linking agents etc. according to our requirement, makes its degradation very difficult [30]. The alarming situation originating from the plastic is due to its non-biodegradable nature, short life and inappropriate dumping such as throwing it in water streams, fields, from

running car windows, filled garbage containers etc. which is a subject of great concern such as environmental, economic and waste management problems [31].

The increasing accumulation of plastic waste in our environment has innumerable effects like soil, air and water pollution which disturbs every habitat in the world. The plastic waste causes floods by clogging drainage system, reduces fertility power of soil, and causes respiratory problems when burnt, reduces the lifespans of animals, and contaminate the water bodies by releasing harmful chemicals when dumped in rivers or oceans [32]. Another problematic thing originating from plastic waste is “the generation of microplastic” which is developed by the degradation of plastic by any of the physical factors such as sunlight, temperature, air, water, microorganism degradation etc. These microplastics are invisible to our eyes but their presence spoils the food chains and ecosystem [33]. The disposal methods such as landfilling, incineration and recycling are not sufficient to overcome this problem. Now it is the time to make people aware of its harmful effects and at the same time, takes some useful scientific steps towards this menace so that the upcoming generations can get a better planet to live on [1, 34].

This growing concern has led to use of degradable polymers, promoted research activity for new degradation methods for plastics and synthesis of new plastic with biodegradable nature or find alternatives to the plastics. Nowadays some products are available in the market which are based on biodegradable plastics such as poly(lactic acid) (PLA), poly(ϵ -caprolactone) (PCL), poly(butylene succinate) (PBS), or poly(butylene succinate-co-butylene adipate) (PBSA) [35,36]. Degradation or the up gradation of the plastic waste by means of various methods such as biodegradation, photolytic, catalytic, thermally etc. is the better solution to minimize this problem. Some synthetic polymers absorb UV radiation and degrade by photolytic, photo and thermo oxidative reactions. Several polymers are susceptible to the microorganism and degrade in a natural way. In this book chapter a brief discussion about the problems originating from the plastic waste, their uses and lifespan in the ambient environment, present approach to deal with the plastic waste and various degradation and up-cycling approaches is presented [29, 30, 37].

2. History of plastic

Mesoamericans are the first who used processed natural rubber for bands, balls etc. in 1600 BC [38]. The first man made polymer is Parkesine (Nitrocellulose) or celluloid, invented by Alexander Parkes in 1856 [21]. It is prepared from cellulose biomolecules. Cellulose is treated with nitric acid and the resulting product is dissolved in alcohol to get harden and elastic material which is easily molded on heating [39]. In 1907, the first synthetic polymer was formed by Belgian Chemist Leo Baekeland by using phenol and formaldehyde i.e. Bakelite. In 1909 Baekeland coined the term “plastic” for the new

group of material. After First World War, polymer technology developed effectively and produced various polymers making life very easy. The mass production of these polymers started during 1940-1950s [21, 22].

3. Types of plastic and their uses

Polymers are known for their diverse application in different fields. Plastics are used in food industry, health care products, building materials, furniture and make living comfortable by making things affordable and cheaper without compromising their strength. Polymers can be divided into different groups based on the different parameters such as on the basis of structure of polymers (linear, Branch chain and cross-linked polymers), mode of polymerization (addition and condensation polymers), thermal behavior (thermoplastic and thermosetting) and source of origin (synthetic and natural polymers) [40, 41]. However, the easier way to classify is the source of origin.

3.1 Natural polymers

These polymers are made by renewable sources such as biomass obtained from tress, microorganisms and animals and are found in abundance in nature. Cellulose is highly abundant polymer formed by the components of the cell wall. Chitin (N-acetylglucosamine) is prepared by the exoskeleton of shrimp and insects, starch is present in potato [42]. Generally, plastics derived from biomass are biodegradable in nature and their use does not harm ecosystem.

3.2 Synthetic polymers

These are man-made polymers and are prepared by non- renewable sources (petrochemicals) and are non-biodegradable and their accumulation in the environment is harmful to ecosystem. Some examples of these polymers are polyethylene, nylon fibre, polyvinylchloride, and polypropylene, polyethylene terephthalate etc. Synthetic polymers are of two types thermoplastic and thermosetting. Thermoplastic polymers are held together by weak interaction such as van der Waal's forces, hydrogen bonding etc. There is an absence of cross links in these polymers. These polymers are moulded repeatedly on heating without breaking i.e. it can be reheated, remould repeatedly while thermosetting polymers can be shaped only once and cannot be remoulded again on heating. Thermosetting polymers develop three dimensional molecular networks on heating. These polymers have strong crosslinking between polymer chain [2, 21, 43]. Hence thermosetting polymers have higher strength than thermoplastic polymers. Some common examples of synthetic polymers are polyethylene, polypropylene, polyethylene terephthalate etc. [44, 46]. Fig.1 indicates the percentage of different plastics demand

distribution on the basis of resin type in global market on 2018 year and Table 1 shows applications of different polymers [43].

Table 1 Shows a list of different plastics with their properties and application.

Types of Plastic	Properties	Applications	References
Polyethylene terephthalate (PET)	Highly flexible, colorless, resistance to moisture, solvent higher strength, toughness, barrier to gas	Used for Carbonated soft drink bottles, sleeping bag, textiles fiber, Containers, fleece clothing, peanut butter and jam bars mouthwash bottles	[22,29]
High-density Polyethylene (HDPE)	Weather proof, low temperature toughness, chemical resistance, permeability to gas,	Mainly used for Packaging of food, fruits, vegetables and drainage pipes, motor oil bottles, shampoo bottles	[22, 46]
Polyvinyl Chlorides (PVC)	Easy processibility, chemical resistance, flexible	Mainly used for electronic pipes, plumbing pipes and shoe soles, automobiles seat covers, juice bottles, medical equipment	[22, 34]
Low- density polyethylene (LDPE)	Quite flexible and tough, ease of processing, moisture and chemical resistance	Container lids, shopping bags, squeezable bottles, shipping envelopes, carpet, furniture, clothing, floor tile, dry cleaning bags, and frozen food wrapper bread bags.	[46,35]
Polypropylene (PP)	Semi-rigid. Translucent. Good chemical resistance. Tough. Good heat resistance.	Drinking straws, medicine bottles, furniture, car batteries, bottles cap, plumbing pipes and carpet	[22,29]
Polystyrene (PS)	Brittle, gamma radiation resistance, rigid, good electrical properties , poor chemical and UV resistance	Food containers laboratory ware, plates, cutlery, disposable tea cups, CD and cassette boxes and certain electronic uses	[22, 35]
Others (often Polycarbonate/ Acrylonitrile Butadiene styrene)	Stiff, rigid, brittle, chemical and stains resistant, good electrical insulators, non-remouldable.	used for making the lens of glasses, rear lights of cars, street lighting, Electronic casing, baby milk bottles, protective headgear,	[22, 29]

Fig.1 Synthetic polymers demand distribution globally on the basis of resin type in 2018.

4. Hazards of plastic

The non- biodegradable nature and toxic components makes plastic a threat to humans, animals and environment. Plastic creates pollution in environment from the manufacturing process to its usage and finally the improper disposal. Plastic releases harmful chemicals in environment such as vinyl chloride, dioxins, benzene, plasticizers, phthalates, bisphenol, formaldehyde and these harmful chemicals reach humans through air, soil, and water. The plastic manufacturing industries release toxic chemicals into the environment such as carbon dioxide, dioxin, and hydrogen cyanide. Methane (greenhouse gas) released during bio-degradation process of plastic causes global warming [47]. Some of the major compounds released into environment include vinyl chloride (in PVC), dioxins (in PVC), benzene (in polystyrene), phthalates and other plasticizers (in PVC and others), formaldehyde, and bisphenol-A, or BPA (in polycarbonate). Many of these are persistent organic pollutants (POPs)-some of the most damaging toxins on the planet, owing to a combination of their persistence in the environment and their high levels of toxicity; however, their unmitigated release into the environment affects all terrestrial and aquatic life with which they come into contact [2, 22].

Fig.2 Harmful effects of plastic on human health. Adapted with permission from Proshad et. al. [50].

Polyethylene is used in shopping bags; toys, bottles etc. and are carcinogenic in nature. Phthalates present in emulsion ink, toys, footwear cause hormonal disturbance, are carcinogenic, reduce sperm count, infertility, and reduce immunity. Polyvinyl alcohol is used in packaging, vinyl siding, utility items and in cosmetics, cause birth, genetic disorders, skin disease, vision problems, deafness, digestion problem, liver related problems and are carcinogenic. Polyvinyl alcohol produces dioxin (potent synthetic chemical) cause cancer, reduce immunity and reproductivity. Bisphenol A is monomeric building block for polycarbonate plastic. During polymerization of polycarbonate, certain percentage of bisphenol A remains unbound. These unbound bisphenol are released from the containers to the food/drinks at elevated temperature. The presences of these chemicals in our body disturb natural hormonal system, causes cancer, reduces immune system, and trigger obesity and diabetes [48, 49]. Fig. 2 [50] shows the harmful effects of plastic on human health.

Plastic waste is also disposed into the oceans. In oceans, the plastic is broken down into small fragments (in micron level) due to the weathering effect. This plastic debris makes

physical harm to marine mammals through ingestion or entanglement such as sea turtle, sea bird, fish and other mammals often ingesting plastic debris mistakenly as food. Such ingestion can lead to internal injuries and infection, malnutrition in mammals when plastic debris is collected in the stomach. Plastic debris releases toxic chemicals which cause death and reproductive failure in mammals. Entanglement in marine system causes suffocation drowning, starvation, vulnerability to predators [47,50].

5. Degradation of plastic

The long term existence of plastic in nature is due to its chemical and physical inert behavior. But plastics are naturally degraded in the environment at a very slow rate. The term “degradation” means any physical and chemical changes in the properties of the material which alter its shape, color, mechanical, optical, electrical and thermal characteristics [21, 29]. The change in properties is also known as “aging”. The degree of degradation of plastic depends on the properties of the polymer as well as the environmental factor to which it is exposed. The environmental factors which help in the degradation of plastics are light, heat, humidity, pH, air, chemicals (acid, base, salt) and biological activity. The molecular weight, chemical structure of the plastic and mixed additives are the factors which effect degradation of plastic [51]. Complete degradation of polymers occurs when it gets converted to water, methane, CO₂, ammonia, hydrogen, sulfide [52]. Salem et. al. [53] studied the biotic and abiotic degradation rate of pro-oxidant filled three types of polyethylene (PE) thin films with 30 and 70 µm thickness. These films are presumed to be oxo- biodegradable in 12 months and they contain nearly 11 wt% CaCO₃. The results of weathering tests revealed that UV radiation triggered the aging mechanism and 50% weight loss occurred after weathering exposer which triggered the fragmentation of plastic films while 83% weight loss occurs after 12 months of soil burial. The degradation of the polymers results in deterioration of functionality of polymers, crazing, erosion, cracking, bond scission, phase transformation, development of new structural unit or functional groups moiety reduces molecular weight of polymers which makes it favorable for biodegradation (degradation by living organism) [54, 55]. The plastic degradation occurs through abiotic and biotic processes [22]. Fig. 3 indicates the degradation route of polymers.

Fig.3 Plastic degradation via various means.

5.1 Abiotic degradation

Abiotic degradation takes place in the intra-molecular level of plastic by physical and chemical process which results discoloration, reduction in molecular weight, size, tensile strength and makes it visually disappear i.e. total loss of its functionality [56, 57]. The physical and chemical aging of plastic converts this inert material into small fragments of lower molecular weight, makes it susceptible for biological degradation. These smaller fragments easily cross the cellular membrane and biodegrade by cellular enzymes in microbial cells i.e. easily metabolized by the microorganism. Hence, abiotic degradation of plastic is a very important step for its biodegradation. Abiotic degradation is initiated by thermal, chemical, hydrolytical and UV-radiation [1, 2]. The beginning of natural degradation of plastic is photodegradation which induces thermo-oxidative degradation. Most of the plastics absorb high energy UV- radiation which provides high activation power to activate their electrons and leads to oxidation, cleavage and further degradation. This causes embrittlement and disintegration of the plastic. Thermal degradation occurs due to overheating of plastic and causes molecular scission. The chemical aging of plastic

is a result of chemical process on plastic. The change in colour and crazing of the surface are the first visual changes of plastic degradation [21, 22]. López et. al. [58] studied the effects of accelerated weathering (AW), natural weathering (NW) and thermal oxidation (TO)[abiotic degradation] on different plastics (high density polyethylene (HDPE), oxodegradable high density polyethylene (HDPE- oxo), compostable plastic, Ecovio ®; metalized polypropylene (PP) and oxodegradable metalized polypropylene (PP-oxo). The plastic films exposed to AW and NW showed general loss in mechanical properties and no substantial loss was found on TO. Oxo-plastics show higher degradation rate than their counterparts.

5.2 Biotic degradation

The degradation of plastics through the living organism such as fungi, bacteria is called biotic degradation. This biological process converts organic materials into water, CO₂, methane, ammonia, hydrogen, energy and new biomass with the help of microorganism. The conversion of materials into small organic or inorganic fragments with the combined effect of abiotic and biotic effects is known as mineralization. Abiotic degradation of plastic converts it into a very small molecular weight fragments which are easily metabolized by microorganism [29-31]. Biotic degradation is of two types: aerobic and anaerobic biodegradation.

5.2.1 Aerobic biodegradation

In aerobic degradation or respiration process, microorganism requires oxygen as an electron acceptor for the deformation of the materials into the smaller products: carbon dioxide (CO₂) and water. Plastics are aerobically degraded in open environment [59, 60].

5.2.2 Anaerobic biodegradation

In anaerobic biodegradation process, microorganisms degrade plastic into carbon dioxide, water and methane in the absence of air (oxygen) [61]. Anaerobic degradation takes place in sediments and landfills. The mineralization of plastic needs several different organisms, some are involved in fragmentation of polymers into monomers, some organisms consume these monomers and excrete smaller compounds, and others use these compounds and excrete biomass and finally few use waste biomass [29]. There are two pathways for anaerobic biodegradation: anaerobic respiration and fermentation. Anaerobic bacteria use nitrate, sulphate, Fe, Mn and CO₂ as an electron acceptor during anaerobic respiration. The organic materials serve as both electron donor as well as electron acceptor and form smaller molecules in anaerobic fermentation process [62, 63].

6. Types of degradation method

Plastic degradation techniques are classified according to their causing factors. These methods are photo, thermo-oxidative, mechano-chemical, catalytic, chemical and biological degradation [30, 64] (Fig.4).

Fig.4 Different types of degradation method.

6.1 Photodegradation

Plastic degradation carried out in presence of light is known as photodegradation. An appropriate amount of energy is absorbed by the photo responsive functional groups present inside the polymer chain. This absorbed light provides activation energy to lead chain breaking into small fragments [65]. Photodegradation is of two types; UV and oxidative degradation. In ultraviolet (UV) degradation, UV light is used to disintegrate polymer materials while in the oxidative method polymers degrade by the combined effect of light and air [21, 30]. UV and infrared portion of light have capabilities to degrade plastic in the presence of air. The exposure to ultraviolet radiation (UV) creates alteration in the properties of plastic by the addition of oxygen molecules into polymer chain, hence this process is known as photo-oxidative degradation. The photo-oxidative degradation is considered as an initial step to degrade plastic into small fragments at ambient condition [66-68]. This degradation results in breaking of polymer chains, generates free radicals, reduces molecular weight and lowering the mechanical strength, variation in optical properties and yellowing the surface of plastic [69-77]. As one or more oxygen molecules enter into the polymer chain, it becomes brittle and easy to degrade into smaller fragments i.e. it is easily metabolized by microorganisms into

carbon dioxide and biomass. However, this process takes a significant time for complete mineralization of plastic, nearly 50 years or more. The photo-oxidative degradation of plastic becomes much more difficult and protracted in subaquatic levels due to lower temperature and oxygen availability and slower rate of hydrolysis of many plastics in ocean [78-82]. Most of the plastics absorb UV radiations (290- 400 nm) and result in bond cleavage in polymer chains. The bond cleavage takes place in the soft segment of plastic, where it generates ester, formate, aldehyde, propyl groups [83]. The wavelength of UV radiation causing plastic destruction is varied according to the nature of bond present in the plastic e.g. polyethylene (300 nm) and 370 nm for polypropylene. The presence of photosensitizers, catalyst residues and metallic impurities are also helpful for initiation of free radicals by homolysis of polymer chain. For example TiO_2 (photosensitizer) helps in the degradation of polyamide and polyolefin at 480 nm and forms highly reactive species such as atomic oxygen, $\cdot\text{OH}$, $\cdot\text{OOH}$ and $\cdot\text{O}_2$ [30]. The presence of carbonyl groups (chromophores) in polymer chains helps to produce free radicals via Norrish type I and II reaction. Photodegradation of polyethylene, polypropylene and polystyrene brings loss in mechanical strength, molecular weight due to extensive bond breaking in polymer chains [71-74]. Chiantore et al. [84] performed photo-oxidative degradation of acrylic and methacrylic polymers by using artificial solar irradiation. FT-IR results show that acrylate units are more reactive towards oxidation than methacrylate.

6.2 Thermo-oxidative degradation

Thermal degradation of polymers results in molecular deterioration due to overheating. The long chains of polymer break into small fragments at high temperature and these fragments react with one another to make change in the properties of plastic. Thermal degradation of plastic results in change in the molecular weight and reduces some physical properties such as ductility and embrittlement, fading of colour, cracking [85]. The products formed on the thermal degradation of the plastic depend on the additives, temperature, time of exposure and environment factors and it is a complex mixture of compounds such as CO , ammonia, furans, dioxin, ketones, hydrogen cyanide, nitriles, aliphatic amines which is toxic and irritating [86]. The photochemical and thermal degradation are similar under normal condition. But these methods are differentiating by some processing steps. The first difference is the initiation step leading to the auto-oxidation and second is that thermal degradation occurs in bulk of the material whereas photodegradation occurs at the surface of the material [87]. The depolymerisation reaction in thermal degradation is not initiated at the terminal end of the macromolecules whereas it takes place in a weak link (a peroxide or ether link) of polymer chain. The polymers synthesized by addition polymerization degrade thermally at very high

temperatures. These are some techniques for the analysis of thermal degradation of polymer for example thermogravimetric analysis (TGA), differential scanning calorimetric (DSC). The impurities present in the polyolefins makes it very susceptible for thermal degradation at high temperature [88]. Polyester degradation results in different types of products such as formaldehyde, acetaldehyde, formic acid, acetic acid, CO₂ and H₂O and some other compounds in small quantity [89].

6.3 Mechano-chemical degradation

It involves the degradation of plastic by mechanical forces and ultrasonic irradiation [90]. Breakdown of molecular chains under shear or mechanical force is often aided by a chemical reaction and is known as mechano-chemical degradation. High speed stirring, regrinding, agitation or ball milling, injection moulding, extrusion are some methods applied for the mechano-chemical degradation of plastic. The basic fundamental is to apply shear force on polymer that breaks polymer chain [91]. Polymer breakdown during mechanical stress is aided by chemical reagents, hence, known as mechano-chemical degradation. Under the influence of mechanical stress, the main backbone of polymer chain (where amorphous region is connected with crystalline region) gets broken into free radicals. These free radicals form peroxy radicals in the presence of oxygen: for example of mastication of rubber [92]. The mastication of rubber in open environment shows polymer chains breaking and origination of plasticity under shear while in N₂ atmosphere it does not show any change in plasticity and molecular weight. On the other hand, in the presence of O₂ it shows fast degradation of rubber. This is because under the influence of mechanical stress, polymer produces free radicals; these radicals react with oxygen (radical scavenger) and lead to the permanent chain breaking whereas nitrogen is not a radical scavenger hence radicals are recombined and show no change in molecular weight [93]. The polymethylmethacrylate (PMMA) decomposes into macro free radicals in the presence of nitroxide (chain terminating agent) which is used in free radical polymerization reaction [94].

6.4 Catalytic degradation

This kind of degradation technique is basically used for the up-cycling of plastic waste. The presence of catalyst helps to transform the plastic waste into highly valued added products such as oil, gases and nanomaterials as well as it gives the selective formation of a particular product; reduce the decomposition temperature of plastic. Some examples of catalysts used in polymer degradation are zeolite and non-zeolite catalysts, transition metal catalysts (Cr, Ni, Mo, Co, Fe) on the support (Al_2O_3 , SiO_2), zeolite and zirconium hydride [95- 98]. Jia et al. [99] converts the polyethylene into liquid fuel and wax by using tandem catalytic cross alkane metathesis method under mild condition. This method is performed in batch autoclaved instrument.

Tiwari and co-workers [100] converted waste plastic except polyvinylchloride and polyethylene terephthalate into fuel range hydrocarbons i.e. petrol, diesel and kerosene etc. by using zeolite catalyst. The effect of polymer catalyst ratio on this conversion is also studied. Ratio (4:1) shows good result for yielding liquid product [100]. Zhang and co-workers [101] produced carbon nanotubes from the pyrolysis of plastic (high density polyethylene) with stainless steel mesh loaded with nickel catalyst.

6.5 Chemical degradation

Polymer disintegration by chemical reaction is a constitutive process. In this process polymers are depolymerized into monomers or oligomers or small chemical compounds. Polymers are made from organic and inorganic moieties which easily break from the polymer chain by using reagents such as water, alcohol, amine, organic and inorganic solvent [102]. Hence chemical degradation is classified into different groups.

6.5.1 Solvolysis or hydrolysis

This method involves depolymerisation of polymers with the help of different solvents. In hydrolysis, water is added to the polymer in the presence of acid or base or neutral environment. For example hydrolysis of polyurethane produced polyol, diamine, and CO_2 under the presence of alkali metal hydroxide catalyst at elevated temperature (250- 450) °C and pressure (15 atm to 50 atm). At higher temperature, recovery yield of polyol is reduced while at lower steam temperature, the produced polyol forms unstable polyurethane foam [103, 104]. The other solvents such as alcohol, amine, glycol and acids are also used for the degradation of plastic or recycling of plastic. But hydrolysis process is very slow as compared to the methanolysis and glycolysis because water is a weak nucleophile and this process also needs high temperature and pressure [105].

6.5.2 Ozonolysis

The degradation of plastic in the presence of ozone causes oxidation of plastic in normal condition. The small concentration of ozone in the air makes significant destruction of polymer in a very short period while other oxidation process at a very slow rate. Polymer exposure to the ozone produces active radicals with change in molecular weight, mechanical and electric properties: saturated polymers forms active oxygen compounds; aliphatic ester, ketones, lactones and aromatic carbonyl associated with styrene produce a variety of carbonyl, ethers, terminal vinyl groups, hydroxyl and unsaturated carbonyl, products based on the polymer type [30]. Ozonolysis of polyvinyl alcohol occurs through the oxidation of alcohol group with the formation of ketone group. This group is further oxidized and leads to the chain scission. FT-IR study reveals the formation of oligomers with numerous ketone group and oligomers with carboxylic end groups [106].

6.6 Biodegradation

Biodegradation method involves the biochemical transformation of materials into small molecular weight fragments that are easily mineralized by microorganism [30]. The biodegradation is also defined as the property of a material to degrade into its constituent molecules by natural process (microbial degradation) and the resulting constituents are non-toxic in nature and these are further used in carbon, nitrogen cycle. Biodegradation rate is influenced by different factors: physical and chemical properties of polymer, types of organism and environmental factors [21]. The large polymeric molecules are not easily biodegraded because they cannot pass through the cellular membrane of microorganism hence polymers must be depolymerized first into small monomers to be metabolized by microorganisms. The initial breakdown can be achieved by the weathering effect such as heat, air, temperature, water etc. [29, 31]. The environmental degradation of synthetic polymers was initially started by the abiotic hydrolysis. Biodegradation of polymers proceeds via four different mechanisms: solubilization, charge formation followed by dissolution, hydrolysis and enzyme catalysed degradation [2, 35]. Hydration of polymers depends on the hydrophilic nature of polymer and results due to the disruption of secondary and tertiary structure stabilized by weak van der Waals forces. Hydration of polymers makes it water soluble and results in bond cleavage by chemical or enzyme catalysed reaction [41, 51]. Ionization, protonation or hydrolysis of the pendent groups (anhydride or ester groups) of polymer chain makes water insoluble polymer soluble; for example polylactic acid become water soluble at high pH. Poly(methacrylate) and poly(methylmethacrylate) are water insoluble polymers and these polymers become water soluble on the hydrolysis of pendent groups (ester) and further ionization of carboxylic groups [53, 56].

Natural polymers undergo degradation by hydrolysis whereas synthetic polymers are water insoluble. They tend to be more crystalline and this property accounts for their water-insolubility [30]. For hydrolysis to occur, polymer must have hydrolytically favorable bonds i.e. reasonably hydrophilic for the access of water. Biodegradable polymers including esters and ester derivative polymers are favorable for this purpose [21, 64]. Microorganisms and enzymes play a very important role for biodegradation process of polymer. Enzymes act as catalysts and a particular enzyme catalyze only a particular reaction. Those, polymers which do not contain any hydrolysable groups such as polyethylene, polypropylene and polystyrene are the most stable polymers and do not degrade easily [21, 30, 53]. Laccase enzyme helps in oxidation process of polyethylene and its degradation process is analysed by gel permeation chromatography. For this process, putative laccase enzyme was isolated from actinomycete *R. ruber*. This enzyme reduces the average molecular weight (20%) and average molecular number (15%) of polyethylene. Laccase usually found in lignin biodegrading fungi, where they function as a catalyst for the oxidation of aromatic compound. However, laccase also shows activity on nonaromatic substrate [21,30]. Lipase enzyme catalyzed degradation of poly (vinylacetate) was studied by Chattopadhyay and Madras [107]. They observed that the ester bond is broken from the side chain of the polymer to produce oligomers with alcohol and acid [107].

Microbial degradation of plastic is achieved by the action of microorganisms such as bacteria, fungi, algae etc. [29]. Microorganisms are best for the contamination destruction because they contain enzymes which help them to easily metabolize it [21]. The conversion of plastic (contamination) into biomass by microorganisms occurs because they utilize contamination as food for their growth and reproduction. Organic contamination fulfills two purpose of microorganisms: first they provide carbon to organisms which is a basic need or basic building block for the development of new cell and second one is that they provide electron to the organism to gain energy [21, 30]. Organisms gain energy by catalyzing exothermic chemical reaction i.e. breaking of chemical bonds, transferring electron from the contamination. Such reactions are known as oxidation-reduction reaction (National Research Council, 1993). The destruction of organic substance in the presence of air is known as aerobic destruction. In this process oxygen molecules are used to oxidize carbon chain and produce CO₂ and remaining carbon is used for cell manufacturing of organisms while oxygen molecules get reduced and produce water. Many organisms cause degradation of plastic in the absence of oxygen molecules are known as anaerobic degradation. In this process nitrate, carbon dioxide, sulphate and some metals such as iron and manganese are used in the place of oxygen and accepting electron from the organic contamination and produce nitrogen gas,

methane, hydrogen sulphide, reduced metals according to the nature of electron acceptor [2, 21, 53]

Polyolefins are non-biodegradable and very strong polymers. Biodegradation of polyethylene occurs by two mechanisms: hydro and oxo- biodegradation. These two mechanisms successfully degrade modified polyethylene (small addition of starch in polyethylene) in the presence of amylase enzyme. The selection of proper test procedure for biodegradation experiment depends on the type of plastic and environment condition. Soil burial and composting methods are used frequently for the determination of degradability behavior of plastic [2, 30, 36]. Biodegradation of plastic can be measure or analysed by weight loss, change in tensile strength, dimensions or physical and chemical properties, carbon dioxide production etc. In soil burial method, degradation test can be performed under natural or laboratory conditions. Testing specimens with definite weight and dimensions is buried in soil in specific depth for a definite time intervals. After a particular time interval, sample is taken out from soil, washed with distilled water and then dried. This dried specimen is analyzed to measure degradation rate. In composting method, dried plastic sample is buried in a definite amount of mature compost in the presence of air and moisture. The nature of compost also affects the degradation rate [30, 21]. Vaverkova and co-workers evaluated the degradation of plastic bags of high density polyethylene (HDPE) with TDPA additive, polypropylene with prooxidant and compostable (starch, polycaprolactone) polymer in composting condition. 12 weeks analysis reveals that the plastic with additives are not degraded (no change in color and physical properties) while other sample are decomposed [108].

7. Factors affecting plastic degradation

Several factors affecting the degradation of plastic (Fig. 5) are as follows:

7.1 Chemical and physical properties of plastic

The biodegradation of plastic is influenced by several factors which include chemical structure, molecular weight, functional groups (hydrophilic and hydrophobic in nature), crystalline and amorphous nature, number and types of bonds, plasticizer or additives added to the plastic [21]. The previous study [60, 78, 109, 110] reveals that plastic with lower molecular weight is more favorable for bio-degradation than the higher molecular weight such as polyolefin with lower molecular weight was degraded by some microorganism much faster than the higher molecular weight polyolefin [30]. The polymer containing only long carbon chains makes it non-susceptible for biodegradation. The introduction of hetero atom and unsaturation makes it susceptible for the thermal and oxidative degradation, and biodegradation. The presence of carbonyl

group and metal- metal bond accelerates the photodegradation of plastic [30, 31]. The amorphous polymers degrade faster than crystalline one due to the permeability of oxygen molecules [21, 22]. Hydrophilic and flexible polymers are degrading much faster than branched polymers. The microbial degradation of the polymers according to the functionality is as follows: ester > etheric > amide > urethane [111]. The additives such as pigments, fillers, catalyst and secondary products remaining during the processing affect the rate of degradation. Metal additives in polyolefins act as pro-oxidant and enhance the thermo-oxidative degradation such as manganese (Mn). Pro-oxidant accelerates the reaction of chain scission and produces small fragments with these moieties –COOH, -OH, C=O [112]. The addition of photo stabilizer (benzotriazoles, hindered amine, phenyl esters etc.) in the polymer reduces photodegradation [29-31].

Fig.5 Factors influencing the biodegradation of polymers.

7.2 Environment factors

The biodegradation of plastic is also affected by environmental condition such as moisture, temperature, pH, oxygen, and suitable population of microorganisms. The hot wet weather is more favourable for all types of degradation rather than hot dry weather [29, 30]. The increase in moisture (above 70%) and temperature increase the rate of hydrolytic degradation, photodegradation and microbial activity [21, 31]. Under high humidity conditions, the water-soluble photo-stabilizers leak out from the plastic and accelerate the photodegradation. Higher temperature and UV radiation enhance thermal

degradation [53]. The thermal stability of polymers (polyethylene, polyethylene terephthalate, polycarbonate polypropylene) is reduced in the presence of air (O_2) compared to the inert environment. Molecular oxygen chemically reacts with the plastic and forms reactive species to enhance the rate of degradation [30].

8. The plastic waste management

8.1 Past scenario

Plastic waste attracts attention of environmentalists due to their durability and non-biodegradability nature and their unavoidable presence. The management rules for plastic waste are not regulated properly and also peoples are not aware of the problems originating from the plastic leakage into the environment. The progressive growth in population, enhanced the consumption rate of plastic which simultaneously increased plastic waste, that promoted the researchers to develop new techniques for plastic disposal /recycling / incineration rather than dumping in the land. Improper dumping of plastic such as throwing everywhere in the land, rivers, drainage system and burning of the plastic in open environment is a serious concern and also creates environmental problems as it impacts natural habitat, wildlife, marine environment and also humans [113]. From the generation of plastic materials (prior to 1980s), nearly all plastic waste was discarded that is it was simply dumped in the land, after 1980s, incineration process was adapted for plastic waste disposal and then recycling process was adapted in 1990s. In 2015, globally 55 % of plastic waste was discarded, 25% was incinerated and 20 % was recycled [20]. In this chapter various methods of plastic disposal and their limitations are briefly discussed.

8.1.1 Landfills

This method is widely used for the disposal of plastic. The drawbacks associated with this method are: landfills occupy a vast area of land which may be utilized for any other productivity means; the occupied space is unavailable for a long time due to the slow degradation rate of plastic, the chemical components and energy exhibited in plastic debris are lost due to this disposal method and the pollutants (phthalates and bisphenol A) are released to the ground water, soil and it also emits toxic gases such as dioxin. Due to the unavailability of O_2 in the land fill area, the plastic degrade anaerobically only [1,114, 115]. Despite these disadvantages the landfill is needed.

8.1.2 Incineration or waste to energy conversion

Incineration method of plastic disposal involves heating of plastic nearly to 1000°C for 1-2 hour and evolved heat is converted into thermal energy or electricity [111]. The PlasticEurope analysis represents that only 16% of plastic waste is combusted with energy recovery while 4% of plastic waste is combusted without energy recovery [111]. This disposal technique reduces plastic waste and generates energy but evolves some air borne mixture of toxic gases such as dioxins ($C_4H_8O_2$) and furans (C_4H_4O) and most commonly the greenhouse gas CO and some other compounds are also emitted according to the type of polymer such as hydrogen cyanide, hydrogen chloride, phosgene, phosphine, phenol, formaldehydes etc. [1, 111]. Hence plastic should be burn in an appropriate chamber not in open environment. With these drawbacks of landfills and incineration method, new method developed for plastic disposal that is recycling [113].

8.1.3 Recycling

Many post-consumer plastic can be used further after reprocessing. This reprocessing gives second life to these materials. There are two types of recycling process first one is mechanical recycling in which plastic is converted to new product without changing the basic structure of materials. Mechanical recycling involves grinding, washing, separating, drying, granulating, and compounding to prepare new product. Injection moulding or extrusion is used for the process of re-melting or reprocessing of products [116]. This recycling requires the separate collection of the plastic which is the main problematic issue during the process. This process helps to regenerate material with small expenditure on the material sorting and cleaning [113]. Another method is chemical recycling in which the plastic is treated with water or any other chemicals at high temperature or pressure, originate lower molecular weight fragments or monomers for the preparation of new materials [1]. There are different depolymerisation routes for the plastic recycling depending on the chemical agent such as solvolysis, ozonolysis, hydrolysis, glycolysis and methanolysis etc. [117]. PET and Nylon 6 polymer is easily depolymerized by the solvolysis using water, alcohol and ether [113]. The advantage of this process is that it is cost effective, very efficient and does not need the separate collection of plastic [113].

8.2 Present approach and prevention for plastic waste management

The above mentioned methods are frequently used today but there are some new techniques also developed for the disposal of plastic. As is known that prevention is better than cure: the new research is focused on this phrase and develops new materials as an alternative for plastic. Here we mention some new disposal techniques and prevention steps.

8.2.1 Organic disposal

This method involves the biochemical transformation of the synthetic and natural plastic into stable small organic fragments by the function of aerobic and anaerobic microorganism in different temperature range. The biological or organic recycling method is divided into two types: composting and anaerobic digestion [113]. Digestion by anaerobic microorganism in the absence of oxygen while composting method is a human derived process performed under a specific set of circumstances in the presence of oxygen and moisture [106, 108, 118]. This method is generally favourable for biodegradable polymers. The presence of bio-component in new generation of plastic shows positive effect on the rate of biodegradation of the plastic and produced biomass with no harmful gases and materials released [2, 30, 117]. Previous study analysis [119,120] reveals that the C/N ratio is a very important factor for the composting process and it should be nearly to 30/1 [113]. Presence of this ratio in biomass prepared for composting method effects the metabolic activity of microorganisms and thus makes composting effective. Kim and Rhee [121] analysis shows that the inadequate availability of key energy component i.e. carbon or key structure components i.e. nitrogen for microorganism may reduce their metabolic activity [119]. The best environment for this method is high temperature, humidity, pH variation, air, light and groups of microorganisms [21, 30, 113]. However, water is a main element for the environmental degradation of plastic. Water effect depends on the physical and chemical properties of plastic. According to the study of Adamcová and co-workers [122], the presence of water molecules initiates the hydrolysis of a bond between polymer and filler and forms active reactive groups such as hydroxyl radical or free radicals. On the other hand, presence of water also helps in the development of microorganisms and proceeds enzymatic reactions causing microbiological degradation.

8.2.2 Reduce the use of plastic

Plastic use can be reduced by choosing alternative or by reducing the use of plastic. For the prevention of plastic eco-friendly approach must be followed: reduce reuse and recycle. Plastic waste can be reduced by dropping plastic use in our life or source reduction occurs by changing the design, manufacturing process. Some steps for the sustainable use of plastic: use cloth bags instead of use and throw carry bags, avoid plastic water bottles and foods in plastic packaging can be introduced. Store food materials in steel or glass container rather than plastic box, don't drink and eat food in use and throw glass and plates. Each single step to the sustainable use of plastic makes our earth and environment safe for all living organisms [123].

8.2.3 Biodegradable plastic

Biodegradable plastics are decomposed by living organism. It is an alternative to the non-biodegradable synthetic plastic [29,30]. These plastics are nearly equivalent to the synthetic petrochemical based plastics in all aspects with an additional quality of being decomposable naturally into safe bio- products in a short period as compared to the conventional plastic [123]. The manufacturing technology of biodegradable plastic are new and very expensive at present. These limitations (high production cost and decreased durability) make it difficult to enter into mainstream yet. Hence the further development of the new technology with energy efficiency and more cost effectiveness is required [113]. The promotion of biodegradable plastic is a progressive and promising prospect and helps to reduce the pressure on the consumption of fossil fuels. The main advantage of these polymers over to conventional polymer is that it is totally manufactured by renewable biomass such as vegetables, tree leaf, food waste, animal shells and by microorganism rather than fossil fuel which are very cheap. There are two main approaches for the development of biodegradable polymer: the production of the synthetic polymer with enhanced degradability nature without reducing the material properties such as addition of functional moieties or bio-component which helps in the deterioration of polymer chain via post polymerization treatments [30, 55, 113]. The main purpose behind this is to enhance the microbial attack on the polymer chain. The degradation rate for conventional plastic will become much better when producing block copolymer with hydrolysable polymeric molecules such as starch, ethylene glycol, lactic acid, caprolactone [124]. New synthetic polyester based biodegradable polymers are frequently used in the packaging industry, paper coating and garbage bags. The polyester blended with polylactic acid and starch- based thermoplastic are degraded into carbon dioxide and water in environment when exposed to microorganism and in compost disposal. Polylactic acid is a synthetic polymer which is completely mineralized and frequently used in medical field since 1990 [113]. Unfortunately, these polymers show less durable nature than synthetic polymer in some cases. The second approach is based on the development of plastic entirely from the biological molecules such as starch, proteins, cellulose acetate, lactic acid, caprolactone and polysaccharides [113, 124]. The mechanical properties of biologically derived polymers have been increased by the addition of plasticizers, nanomaterials or by controlling the production condition.

Example of bioplastic or sustainable polymer is poly(hydroxyalkanoates) (PHAs), which is synthesized by many bacteria such as *Pseudomonas*, *Bacillus*, *Ralstonia*, *Aeromonas*, *Rhodobacter*, and *Azotobacter* as well as certain Archaea, such as *Haloferaxsulfurifontis* are used in packaging, biomedical and coating application [125].

There are some obstacles which prevent the use of biodegradable polymers: the cost of biodegradable polymers is higher than petrochemical based polymers. Another drawback is limited availability of monomers, their processability, cost, performance limitation and rate of degradation. Bio-plastic such as starch and cellulose are not favorable for mechanical recycling as well as for incineration because their calorific value is very low. Next obstacle is the absence of suitable infrastructure for the development of biodegradable polymers such as higher cost of manufacturing technology of biodegradable polymers. Hence further research is required for making the biodegradable polymers manufacturing cost more effective.

8.2.4 Up conversion of plastic into value added product

Waste conversion into wealth is the basis of upcycling technique. In upcycling process, plastic is converted into a better quality and higher value products. Upcycling helps in plastic waste management by convert plastic into value added products such as chemicals for monomer feedstock, fuels, carbon nanomaterials, etc. due to the presence of carbon content in major amount [113]. For examples polyethylene contains 85.6%, polystyrene (92.2%) polypropylene 85.6 %. carbon content [126]. Hence it can be used as a carbon source for carbon based value added products for examples activated carbon, carbon nanotubes, graphene, carbon fibers etc. Pandey et. al. [127] reported an invincible method for the development of graphene nanosheets in bulk amount from plastic waste by two step pyrolysis process: first one at 400°C and second is at 750°C in presence of catalyst (nanoclay). The obtained black residue is graphene nanosheets with confirmation from Raman spectroscopy data. The methodology flow chart of graphene nanosheets formation is described in (Fig. 6) [127]. The non-wetting nature of plastic makes its use in road construction. Water penetration across the bitumen film makes pothole in road however, plastic coating over the aggregates prevents the penetration of water due to the non-wetting nature of plastic. Polymers also have higher softening temperature which reduces the stripping of aggregates during summer season [113]. Rao and co-workers [128] and team prepared oil from waste plastic. His team took 1 ton of plastic waste after washing and drying processing. This plastic mixture was pyrolyzed in the presence of catalyst (aluminum silicates nearly 2.5% of the plastic mass) at (603- 723) K. Three products are obtained: obtained pyrolysis oil (60- 70%), gas (15-20%) and carbon black (20-30%). Oil mixture contains different ratio of material 40% oil+60% petrol, 10% oil + 90% diesel, 30% oil + 70% diesel and 50% oil + 50% diesel and various characteristic confirms the presence of pure fuel oil.

Fig.6 The methodology flow chart for the production of graphene nano sheets, (a) physical state of carbon residue obtained from slow pyrolysis, (b) Skeleton structure of graphene nano sheets after fast heating. Adapted with permission from Pandey et. al. [127].

Conclusion and future prospective

The indiscriminate use of plastic and its totally inert behavior to all environmental factors, leads the plastic waste generation all over the world. Waste plastic produces so many harmful effects such as generation of toxic pollutants, spoiling the natural behavior of soil, water and air, creates disturbance to the ecosystem, and causes many diseases in humans and mammals. This inert material is not degrade naturally in the environment or takes nearly 400 years or more to biodegrade. Hence different degradation approaches are currently used to degrade plastic waste. By means of these methods it is possible to manage or overcome this growing problem. However, footprints of plastic in the environment can be reduced by adapting some effective steps such as reduce the use of plastic in our daily life, use biodegradable material for grocery shopping or dispose used plastic in proper manner that it can further be utilized in material processing. The researchers are continuously working to find the alternative for plastic. For the fulfillment of this purpose they are trying to modify synthetic polymers with natural polymers or additives which imitate the biodegradation rate or producing biopolymers with desirable

physical and mechanical properties to deliver real commercial benefits as well as evaluating the resulting polymers for degradation and life span.

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References

- [1] H. K. Webb, J. Arnott, R. J. Crawford, E. P. Ivanova, Plastic degradation and its environmental implications with special reference to poly (ethylene terephthalate), *Polymers*. 5 (2013) 1-18. <https://doi.org/10.3390/polym5010001>
- [2] V. M. Pathak, Navneet, Review on the current status of polymer degradation: a microbial approach, *Bioresour. Bioprocess*. 4 (2017) 1-31. <https://doi.org/10.1186/s40643-017-0145-9>
- [3] J. R. Fried, *Polymer science & technology: Introduction to polymer science*, third ed., New Jersey, 1995.
- [4] G. Scott, *Polymers and the Environment: Polymers in modern life*, first ed., Cambridge, UK, 1999.
- [5] R. B. Seymour, Polymer science before and after 1899: notable developments during the lifetime of Maurits Dekker, *J. Macromol. Sci. Chem*. 26 (1989) 1023-1032. <https://doi.org/10.1080/00222338908052032>
- [6] S. Mukherjee, S. Chatterjee, A comparative study of commercially available plastic carry bag biodegradation by microorganisms isolated from hydrocarbon effluent enriched soil. *Int. J. Curr. Microbiol. App. Sci*. 3(2014) 318-325.
- [7] J. G. Speight, *Handbook of industrial hydrocarbon processes*, first ed., USA, 2011
- [8] L. Andrady, M. A. Neal, Applications and societal benefits of plastics, *Philos. Trans. R. Soc. Lond. B. Biol. Sci*. 364(2009) 1977-1984. <https://doi.org/10.1098/rstb.2008.0304>
- [9] M. Tosin, M. Weber, M. Siotto, C. Lott, F. Degli-Innocenti, Laboratory test methods to determine the degradation of plastics in marine environmental conditions, *Front. Microbiol*. 3 (2012) 1-9. <https://doi.org/10.3389/fmicb.2012.00225>
- [10] D. W. Laist, Overview of the biological effects of lost and discarded plastic debris in the marine environment, *Mar. Pollut. Bull*. 18 (1987) 319-326. [https://doi.org/10.1016/S0025-326X\(87\)80019-X](https://doi.org/10.1016/S0025-326X(87)80019-X)
- [11] A. T. Pruter, Sources, quantities and distribution of persistent plastics in the marine environment. *Mar. Pollut. Bull*. 18(1987) 305-310. [https://doi.org/10.1016/S0025-326X\(87\)80016-4](https://doi.org/10.1016/S0025-326X(87)80016-4)

- [12] C.J. Moore, S.L. Moore, M. K. Leecaster, S.B. Weisberg, A comparison of plastic and plankton in the North Pacific Central Gyre, *Mar. Pollut. Bull.* 42(2001) 1297–1300. [https://doi.org/10.1016/s0025-326x\(01\)00114-x](https://doi.org/10.1016/s0025-326x(01)00114-x)
- [13] J. G. Derraik, The pollution of the marine environment by plastic debris: a review, *Mar. Pollut. Bull.* 44(2002) 842-852. [https://doi.org/10.1016/S0025-326X\(02\)00220-5](https://doi.org/10.1016/S0025-326X(02)00220-5)
- [14] R. C. Thompson, Y. Olsen, R. P. Mitchell, A. Davis, S. J. Rowland, A. W. G. John, D. McGonigle, A. E. Russell, Lost at sea: where is all the plastic?, *Science*. 304(2004) 838-838. <https://doi.org/10.1126/science.1094559>
- [15] C. J. Moore, Synthetic polymers in the marine environment: a rapidly increasing, long-term threat, *Environ. Res.* 108 (2008)131-139. <https://doi.org/10.1016/j.envres.2008.07.025>
- [16] D. K. A. Barnes, F. Galgani, R. C. Thompson, M. Barlaz, Accumulation and fragmentation of plastic debris in global environments, *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* 364 (2009) 1985–1998. <https://doi.org/10.1098/rstb.2008.0205>
- [17] M. R. Gregory, Environmental implications of plastic debris in marine settings—entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions, *Philos. Trans. R. Soc. Lond. B. Biol. Sci.* 364 (2009) 2013–2025. <https://doi.org/10.1098/rstb.2008.0265>
- [18] K. L. Law, S. Morét-Ferguson, N.A. Maximenko, G. Proskurowski, E. E. Peacock, J. Hafner, C. M. Reddy, Plastic accumulation in the North Atlantic Subtropical Gyre, *Science*.329(2010) 1185–1188. <https://doi.org/10.1126/science.1192321>
- [19] Regional consumption of plastic materials per capita 2015. <https://www.statista.com/statistics/270312/consumption-of-plastic-materials-per-capita-since-1980/>, 2016 (accessed March 2016).
- [20] Plastic pollution- Our world in data. <https://ourworldindata.org/plastic-pollution>, 2018 (accessed September 2018)
- [21] R. Chandra, *Environmental waste management: The role of microbes in plastic degradation*. first ed., India, 2015.
- [22] S. Goel, *Advances in solid and hazardous waste management: degradation of plastics*, first ed., Capital Publishing Company, New Delhi, India, 2017.
- [23] The plastics industry in India: An overview. <https://www.bpf.co.uk/article/the-plastics-industry-in-india-an-overview-446.aspx>, 2010 (accessed 2010).
- [24] An Indian consumes 11kg plastic every year and an average American 109 kg. <https://www.downtoearth.org.in/news/waste/an-indian-consumes-11-kg-plastic-every-year-and-an-average-american-109-kg-60745>, 2018, (accessed June 2018).
- [25] Tackling increasing plastic waste- World Bank Group. http://datatopics.worldbank.org/whatawaste/tackling_increasing_plastic_waste.html, 2018, (accessed 2018).

- [26] Beat plastic pollution: This world environment day.
<https://www.unenvironment.org/interactive/beat-plastic-pollution/>, 2018 (accessed 2018).
- [27] M. Eriksen, L. C. Lebreton, H. S. Carson, M. Thiel, C. J. , Moore, J. C. Borerro, F. Galgani, P. G. Ryan, J. Reisser, Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea, *PLoS ONE*. 9(2014).
<https://doi.org/10.1371/journal.pone.0111913>
- [28] S. Doetsch-Kidder, *Social change and intersectional activism: The spirit of social movement*, US, 2012.
- [29] A.A. Shah, F. Hasan, A. Hameed, S. Ahmed, Biological degradation of plastics: A comprehensive review, *Biotechnol. Adv.* 26 (2008) 246–265.
<https://doi.org/10.1016/j.biotechadv.2007.12.005>
- [30] B. Singh, N. Sharma, Mechanistic implications of plastic degradation, *Polym. Degrad. Stab.*, 93(2008) 561-584.
<https://doi.org/10.1016/j.polymdegradstab.2007.11.008>
- [31] S. K. Kale, A. G. Deshmukh, M. S. Dudhare, V. B. Patil, Microbial degradation of plastic: a review, *J. Biochem. Technol.* 6 (2015) 952-961.
- [32] Ejim, E. Patrick, J. Eze, Plastic pollution management: a panacea for nigeria's untapped waste to wealth growth; a study of some selected urban cities in south east nigeria-enugu, owerri, awka and umuahia, *Adv. J. Man. Acc. Fin.* 4 (2019) 21-30.
- [33] T. Bond, V. Ferrandiz-Mas, M. Felipe-Sotelo, E. van Seville, The occurrence and degradation of aquatic plastic litter based on polymer physicochemical properties: a review, *Crit. Rev. Env. Sci. Tec.* 48 (2018) 685-722.
<https://doi.org/10.1080/10643389.2018.1483155>
- [34] R. K. Singh, B. Ruj, Plastic waste management and disposal techniques-Indian scenario, *Int. J. Plast. Technol.* 19 (2015) 211-226. <https://doi.org/10.1007/s12588-015-9120-5>
- [35] Y. Tokiwa, B. P. Calabia, C. U. Ugwu, S. Aiba, Biodegradability of plastics, *Int. J. Mol. Sci.* 10 (2009) 3722-3742. <https://doi.org/10.3390/ijms10093722>
- [36] Y. Zheng, E. K. Yanful, A. S. Bassi, A review of plastic waste biodegradation, *Crit. Rev. Biotechnol.*, 25 (2005) 243-250.
<https://doi.org/10.1080/07388550500346359>
- [37] A. Kulkarni, H. Dasari, Current status of methods used in degradation of polymers: A review, In. *MATEC Web of Conferences*. 144 (2018) 02023.
<https://doi.org/10.1051/mateconf/201814402023>
- [38] D. Hosler, S. L. Burkett, M. J. Tarkanian, Prehistoric polymers: rubber processing in ancient Mesoamerica, *Science*. 284 (1999) 1988-1991.
<https://doi.org/10.1126/science.284.5422.1988>
- [39] Celluloid. <https://www.merriam-webster.com/dictionary/celluloid>

- [40] S. Tripathi, A. Yadav, Bioremediation of industrial pollutants: plastic waste: environmental pollution, health hazards and biodegradation strategies, New Delhi, India, 2016.
- [41] M. Raziya-fathima, P. K. Praseetha, I. R. S. Rimal, Microbial degradation of plastic waste: a review, *J. Pharm. Chem. Biol. Sci.* 4 (2016) 231-242. <https://doi.org/10.17352/ojeb.000010>
- [42] R. Premraj, M. Doble, Biodegradation of polymer, *Indian J. Biotechnol.* 4 (2005) 186-193.
- [43] Plastics-the Facts 2019. An analysis of European plastics production, demand and waste data.
- [44] N. Pandey, C. Tewari, S. Dhali, B. S. Bohra, S. Rana, S. P. S. Mehta, S. Singhal, A. Chaurasia, N. G. Sahoo, Effect of graphene oxide on the mechanical and thermal properties of graphene oxide/hytrex nanocomposites, *J. Thermoplast. Compos. Mater.* (2019) 1-13. <https://doi.org/10.1177/0892705719838010>.
- [45] I. L. Nerland, C. Halsband, I. Allan, K. V. Thomas, Microplastics in marine environments: Occurrence, distribution and effects, (2014) 1-71.
- [46] D. Danso, J. Chow, W. R. Streita, Plastics: environmental and biotechnological perspectives on microbial degradation, *Appl. Environ. Microbiol.* 85 (2019) 1-14. <https://doi.org/10.1128/AEM.01095-19>
- [47] R. E. Hester, R. M. Harrison, *Marine Pollution and Human Health*, first ed., 2011
- [48] V. Koushal, R. Sharma, M. Sharma, R. Sharma, V. Sharma, Plastics: Issues challenges and remediation, *Int. J. Waste Resources.* 4 (2014) 2-6. <https://doi.org/10.4172/2252-5211.1000134>
- [49] P. Pavani, T. R. Rajeswari, Impact of plastics on environmental pollution, *J. chem. pharm. sci.* (2014) 87-93
- [50] R. Proshad, T. Kormoker, M. S. Islam, M. A. Haque, M. M. Rahman, M. M. R. Mithu, Toxic effects of plastic on human health and environment: A consequences of health risk assessment in Bangladesh, *Int. J. Health Serv.* 6 (2018) 1-5. <https://doi.org/10.14419/ijh.v6i1.8655>
- [51] R. Mohee, G. D. Unmar, A. Mudhoo, P. Khadoo, Biodegradability of biodegradable/degradable plastic materials under aerobic and an aerobic conditions, *Waste Manag.* 28 (2008) 1624- 1629. <https://doi.org/10.1016/j.wasman.2007.07.003>
- [52] J. P. Eubeler, S. Zok, M. Bernhard, T. P. Knepper, Environmental biodegradation of synthetic polymers I. Test methodologies and procedures, *Trends Anal. Chem.* 28 (2009) 1057-1072. <https://doi.org/10.1016/j.trac.2009.06.007>
- [53] S. M. Al-Salem, A. Al-Hazza'a, H. J. Karam, M. H. Al-Wadi, A. T. Al-Dhafeeri, A. A. Al-Rowaih, Insights into the evaluation of the abiotic and biotic degradation rate of commercial pro-oxidant filled polyethylene (PE) thin films, *J Environ. Manage.* 250 (2019). <https://doi.org/10.1016/j.jenvman.2019.109475>

- [54] J. Pospisil, S. Nespurek, R. Pfaendner, H. Zweifel, Material recycling of plastics waste for demanding applications: upgrading by restabilization and compatibilization. *Trends Polym. Sci.* 5 (1997) 294-300.
- [55] J. A. Glaser, Biological degradation of polymers in the environment, Intech Open. 2019. <https://doi.org/10.5772/intechopen.85124>
- [56] A. Sivan, New perspectives in plastic biodegradation, *Curr. Opin. Biotech.* 22(2011) 422-426. <https://doi.org/10.1016/j.copbio.2011.01.013>
- [57] P. K. Roy, M. Hakkarainen, I. K. Varma, A. C. Albertsson, Degradable Polyethylene: Fantasy or Reality, *Environ. Sci. Technol.* 45 (2011) 4217–4227. <https://doi.org/10.1021/es104042f>
- [58] Y. G. Ángeles-López, A. M. Gutiérrez-Mayen, M. Velasco-Pérez, M. Beltrán-Villavicencio, A. Vázquez-Morillas, M. Cano-Blanco, Abiotic degradation of plastic films, *J. Phys. Conf. Ser.* 792 (2017).
- [59] P. Nayak A. Tiwari, Biodegradability of polythene and plastic by the help of microorganism: A way for brighter future, *J. Environ Anal. Toxicol.* 1 (2011). <https://doi.org/10.4172/2161-0525.1000111>
- [60] J. D. Gu, Microbiological deterioration and degradation of synthetic polymeric materials: recent research advances, *Int. Biodeter. Biodegr.* 52 (2003) 69-91. [https://doi.org/10.1016/S0964-8305\(02\)00177-4](https://doi.org/10.1016/S0964-8305(02)00177-4)
- [61] P.S. Chahal, D. S. Chahal, G. André, Cellulase production profile of *Trichoderma reesei* on different cellulosic substrates at various pH levels, *J. Ferment. Bioeng.* 74 (1992) 126–128. [https://doi.org/10.1016/0922-338X\(92\)80015-B](https://doi.org/10.1016/0922-338X(92)80015-B)
- [62] J. D. Gu, R. Mitchell, Biodeterioration, in M. Dworkin, S. Falkow, E. Rosenberg, K. H. Schleifer, E. Stackebrandt (Eds.), *The Prokaryotes*, Springer, New York, 2006, pp.864-903.
- [63] S. K. Mohan, T. Srivastava, Microbial deterioration and degradation of polymeric materials, *J. Biochem. Technol.* 2(2011) 210–215. <https://doi.org/10.12691/jaem-5-1-2>
- [64] A. Kulkarni, H. Dasari, Current status of methods used in degradation of polymers: A review, *MATEC Web of Conf.* 144 (2018) 02023. <https://doi.org/10.1051/mateconf/201814402023>
- [65] I. Kyrikou, B. Briassoulis, Biodegradation of agricultural plastic films: a critical review, *J. Polym. Environ.* 15(2007) 125-150. <https://doi.org/10.1007/s10924-007-0053-8>
- [66] B. Rånby, Photodegradation and photo-oxidation of synthetic polymers, *J. Anal. Appl. Pyrol.* 15 (1989) 237-247. [https://doi.org/10.1016/0165-2370\(89\)85037-5](https://doi.org/10.1016/0165-2370(89)85037-5)
- [67] J. T. Jensen, J. Kops, Photochemical degradation of blends of polystyrene and poly(2, 6-dimethyl-1, 4-phenylene oxide), *J. Polym. Sci. Polym. Chem.* 18 (1980) 2737-2746. <https://doi.org/10.1002/pol.1980.170180830>

- [68] G. E. Sheldrick, O. Vogl, Induced photodegradation of styrene polymers: a survey, *J. Polym. Eng. Sci.* 16 (2004) 65- 73. <https://doi.org/10.1002/pen.760160202>
- [69] J. W. Martin, J. W. Chin, T. Nguyen, Reciprocity law experiments in polymeric photodegradation: a critical review, *Prog. Org. Coat.* 47 (2003) 292-311. <https://doi.org/10.1016/j.porgcoat.2003.08.002>
- [70] J. Czerný, Thermo-oxidative and photo-oxidative aging of polypropylene under simultaneous tensile stress, *J. Appl. Polym. Sci.* 16 (1972) 2623-2632. <https://doi.org/10.1002/app.1972.070161015>
- [71] M. Obadal, R. Čermák, M. Raab, V. Verney, S. Commereuc, F. Fraïsse, Study on photodegradation of injection-moulded β -polypropylenes, *Polym. Degrad. Stab.* 91 (2006) 459-463. <https://doi.org/10.1016/j.polymdegradstab.2005.01.046>
- [72] S. H. Hamid, W. H. Prichard, Mathematical modeling of weather-induced degradation of polymer properties, *J. Appl. Polym. Sci.*, 43 (1991) 651-678. <https://doi.org/10.1002/app.1991.070430404>
- [73] A. Marek, L. Kaprálková, P. Schmidt, J. Pfleger, J. Humlíček, J. Pospíšil, J. Pilař, Spatial resolution of degradation in stabilized polystyrene and polypropylene plaques exposed to accelerated photodegradation or heat aging, *Polym. Degrad. Stab.* 91(2006) 444-458. <https://doi.org/10.1016/j.polymdegradstab.2005.01.048>
- [74] A. L. Andrady, J. E. Pegram, Y. Tropsha, Changes in carbonyl index and average molecular weight on embrittlement of enhanced-photodegradable polyethylenes, *J. Environ. Polym. Degrad.* 1 (1993) 171-179. <https://doi.org/10.1007/BF01458025>
- [75] A. Ghaffar, A. Scott, G. Scott, G., The chemical and physical changes occurring during UV degradation of high impact polystyrene, *Eur. Polym. J.*, 11 (1975) 271-275. [https://doi.org/10.1016/0014-3057\(75\)90075-0](https://doi.org/10.1016/0014-3057(75)90075-0)
- [76] Y. Nagai, T. Ogawa, Y. Nishimoto, F. Ohishi, Analysis of weathering of a thermoplastic polyester elastomer II. Factors affecting weathering of a polyether–polyester elastomer, *Polym. Degrad. Stab.* 65 (1999) 217-224. [https://doi.org/10.1016/S0141-3910\(99\)00007-5](https://doi.org/10.1016/S0141-3910(99)00007-5)
- [77] A. Torikai, Wavelength sensitivity of photodegradation of polymer, in: S. H. Hamid (Eds.), *Handbook of polymer degradation*, New York: Markel Dekker; 2000, pp. 573- 604
- [78] K. Yamada-Onodera, H. Mukumoto, Y. Katsuyaya, A. Saiganji, Y. Tani, Degradation of polyethylene by a fungus, *Penicilliumsimplicissimum* YK, *Polym. Degrad. Stab.* 72 (2001) 323-327. [https://doi.org/10.1016/S0141-3910\(01\)00027-1](https://doi.org/10.1016/S0141-3910(01)00027-1)
- [79] Y. Zheng, E. K. Yanful, A. S. Bassi, A review of plastic waste biodegradation, *Crit. Rev. Biotechnol.*, 25 (2005) 243-250. <https://doi.org/10.1080/07388550500346359>
- [80] A. L. Andrady, Microplastics in the marine environment, *Mar. Pollut. Bull.*, 62 (2011) 1596-1605. <https://doi.org/10.1016/j.marpolbul.2011.05.030>

- [81] J. M. Raquez, A. Bourgeois, H. Jacobs, P. Degée, M. Alexandre, P. Dubois, Oxidative degradations of oxodegradable LDPE enhanced with thermoplastic pea starch: Thermo-mechanical properties, morphology, and UV-ageing studies, *J. Appl. Polym. Sci.* 122 (2011) 489-496. <https://doi.org/10.1002/app.34190>
- [82] R. J. Müller, I. Kleeberg, W. D. Deckwer, Biodegradation of polyesters containing aromatic constituents, *J. Biotechnol.* 86 (2001) 87-95. [https://doi.org/10.1016/S0168-1656\(00\)00407-7](https://doi.org/10.1016/S0168-1656(00)00407-7)
- [83] Y. Nagai, D. Nakamura, T. Miyake, H. Ueno, N. Matsumoto, A. Kaji, Photo degradation mechanisms in poly(2,6-butylenenaphthalate-co tetramethyleneglycol) (PBN-PTMG). II: wavelength sensitivity of the photodegradation, *Polym. Degrad. Stab.* 88 (2005) 251-255
- [84] O. Chiantore, L. Trossarelli, M. Lazzari, Photooxidative degradation of acrylic and methacrylic polymers, *Polymer*, 41 (2000) 1657-1668. [https://doi.org/10.1016/S0032-3861\(99\)00349-3](https://doi.org/10.1016/S0032-3861(99)00349-3)
- [85] Thermal Degradation of plastic. http://www.appstate.edu/~clementsjs/polymer-properties/zeus_thermal_degradation.pdf, 2005 (accessed 2005).
- [86] MSDS- Nylon 6. <http://skipper.physics.sunysb.edu/HBD/MSDS/NylonMSDS.pdf>, 2001. (accessed 2001).
- [87] D. R. Tayler, Mechanistic aspects of the effect of stress on the rate of photochemical degradation reactions in polymers, *J Macromol. Sci. Part C. Polym. Rev.* 44 (2004) 351-388. <https://doi.org/10.1081/MC-200033682>
- [88] F. Khabbaz, A. C. Albertsson, S. Karlsson, Chemical and morphological changes of environmentally degradable polyethylene films exposed to thermo-oxidation. *Polym. Degrad. Stab.* 63(1999) 127-138. [https://doi.org/10.1016/S0141-3910\(98\)00082-2](https://doi.org/10.1016/S0141-3910(98)00082-2)
- [89] H. V. Boenig, Unsaturated polyesters: structure and properties, London, New York, 1964.
- [90] J. Li, S. Guo, X. Li, Degradation kinetics of polystyrene and EPDM melts under ultrasonic irradiation, *Polym. Degrad. Stab.* 89 (2006) 6-14. <https://doi.org/10.1016/j.polymdegradstab.2004.12.017>
- [91] K. Baranwal, Mechanochemical degradation of an EPDM polymer, *J. Appl. Polym. Sci.* 12 (2003) 1459-1469. <https://doi.org/10.1002/app.1968.070120617>
- [92] L. C. Bateman, Chemistry and physics of rubber-like substances, first ed., (1963)
- [93] P. Ghosh, Polymer science and technology of plastics, rubbers, blends and composites, third ed., New Delhi, 1990.
- [94] G. Schmidt-Naake, M. Drache, M. Weber, Combination of Mechanochemical Degradation of Polymers with Controlled Free-Radical Polymerization, *Macromol. Chem. Phys.* 203(2002) 2232-2238. [https://doi.org/10.1002/1521-3935\(200211\)203:15<2232::AID-MACP2232>3.0.CO;2-N](https://doi.org/10.1002/1521-3935(200211)203:15<2232::AID-MACP2232>3.0.CO;2-N)

- [95] Y. H. Lin, H. Y. Yen, Fluidised bed pyrolysis of polypropylene over cracking catalysts for producing hydrocarbons, *Polym. Degrad. Stab.* 89 (2005) 101-108. <https://doi.org/10.1016/j.polymdegradstab.2005.01.006>
- [96] P. T. Williams, R. Bagri, Hydrocarbon gases and oils from the recycling of polystyrene waste by catalytic pyrolysis, *Int. J. Energy Res.* 28 (2003) 31-44. <https://doi.org/10.1002/er.949>
- [97] J. R. Kim, J. H. Van, D. W. Park, M. H. Lee, Catalytic degradation of mixed plastics using natural clinoptilolite catalyst. *React. Kinet. Catal. Lett.* 81 (2004) 73-81. <https://doi.org/10.1023/B:REAC.0000016519.59458.08>
- [98] W. Kaminsky, F. Hartmann, New pathways in plastics recycling, *Angew. Chem. Int. Ed.*, 39 (2000) 331-333. [https://doi.org/10.1002/\(SICI\)1521-3773\(20000117\)39:2%3C331::AID-ANIE331%3E3.0.CO;2-H](https://doi.org/10.1002/(SICI)1521-3773(20000117)39:2%3C331::AID-ANIE331%3E3.0.CO;2-H)
- [99] X. Jia, C. Qin, T. Friedberger, Z. Guan, Z. Huang, Efficient and selective degradation of polyethylenes into liquid fuels and waxes under mild conditions, *Sci. Adv.*, 2 (2016) 1501-1591. <https://doi.org/10.1126/sciadv.1501591>
- [100] D. C. Tiwari, E. Ahmad, K. K. Singh, Catalytic degradation of waste plastic into fuel range hydrocarbons, *Int. J. Chem. Res.* 1 (2009) 31-36. <https://doi.org/10.9735/0975-3699.1.2.31-36>
- [101] Y. Zhang, M. A. Nahil, C. Wu, P. T. Williams, Pyrolysis–catalysis of waste plastic using a nickel–stainless-steel mesh catalyst for high-value carbon products, *Environ. Technol.* 38 (2017) 2889-2897. <https://doi.org/10.1080/09593330.2017.1281351>
- [102] V. Sinha, M. R. Patel, J. V. Patel, PET waste management by chemical recycling: a review. *J. Polym. Environ.* 18 (2010) 8-25. <https://doi.org/10.1007/s10924-008-0106-7>
- [103] D. Simón, A. M. Borreguero, A. De Lucas, and J. F. Rodríguez, Recycling of polyurethanes from laboratory to industry, a journey towards the sustainability, *J. Waste Manag.* 76 (2018) 147-171. <https://doi.org/10.1016/j.wasman.2018.03.041>
- [104] W. Yang, Q. Dong, S. Liu, H. Xie, L. Liu, J. Li, Recycling and disposal methods for polyurethane foam wastes, *Procedia Environ. Sci.* 16 (2012) 167-175. <https://doi.org/10.1016/j.proenv.2012.10.023>
- [105] S. Thomas, A. V. Rane, K. Kanny, V. K. Abitha, M. G. Thomas, Recycling of Polyurethane Foams. William Andrew, first ed., 2018
- [106] F. Cataldo, G. Angelini, Some aspects of the ozone degradation of poly (vinyl alcohol), *Polym. Degrad. Stab.* 91 (2006) 2793-2800. <https://doi.org/10.1016/j.polymdegradstab.2006.02.018>
- [107] S. Chattopadhyay, G. Madras, Kinetics of the enzymatic degradation of poly(vinyl acetate) in solution, *J. Appl. Polym. Sci.* 89 (2003) 2579-2582. <https://doi.org/10.1002/app.12403>

- [108] M. Vaverková, D. Adamcová, J. Kotovicová, F. Toman, Evaluation of biodegradability of plastics bags in composting conditions, *Ecol. Chem. Eng., S*, 21 (2014) 45-57. <https://doi.org/10.2478/eces-2014-0004>
- [109] Y. Tokiwa, T. Suzuki, Hydrolysis of Polyesters by *Rhizopusdelemar* Lipase, *Agric. Biol. Chem.*, 42 (1978) 1071- 1072. <https://doi.org/10.1271/bbb1961.42.1071>
- [110] F. Kawai, M. Watanabe, M. Shibata, S. Yokoyama, Y. Sudate, S. Hayashi, Comparative study on biodegradability of polyethylene wax by bacteria and fungi, *Polym. Degrad. Stab.* 86 (2004) 105-114. <https://doi.org/10.1016/j.polymdegradstab.2004.03.015>
- [111] M. Mierzwa-Hersztek, K. Gondek, M. Kopeć, Degradation of polyethylene and biocomponent-derived polymer materials: An Overview, *J Polym. Environ.* 27 (2012) 600-611. <https://doi.org/10.1007/s10924-019-01368-4>
- [112] I. Jakubowicz, Evaluation of degradability of biodegradable polyethylene (PE), *Polym. Degrad. Stabil.* 80 (2003) 39-43. [https://doi.org/10.1016/S0141-3910\(02\)00380-4](https://doi.org/10.1016/S0141-3910(02)00380-4)
- [113] R. K. Singh, B. Ruj, Plasticwaste management and disposal techniques-Indian scenario, *Int. J. Plast. Technol.* 19 (2015) 211-226. <https://doi.org/10.1007/s12588-015-9120-5>
- [114] B. Tansel, B.S. Yildiz, Goal-based waste management strategy to reduce persistence of contaminants in leachate at municipal solid waste landfills, *Environ. Dev. Sustain.* 13(2011). 821-831. <https://doi.org/10.1007/s10668-011-9290-z>
- [115] E.W. Tollner, P.A. Annis, K.C. Das, Evaluation of strength properties of polypropylene-basedpolymers in simulated landfill and oven conditions, *J. Environ. Eng.* 137 (2011) 291–296
- [116] N. Miskolczi, L. Bartha, A. Angyal, High energy containing fractions from plastic wastes by their chemical recycling, *Macromol. Symp.* 245-246 (2006) 599-606. <https://doi.org/10.1002/masy.200651386>
- [117] E. Butler, G. Devlin, K. McDonnell, Waste polyolefins to liquid fuels via pyrolysis: review of commercial state-of-the-art and recent laboratory research, *Waste Biomass Valor.*, 2 (2011) 227-255. <https://doi.org/10.1007/s12649-011-9067-5>
- [118] B. Herman, R. Biczak, P. Rychter, M. Kowalczyk, Degradation of selected synthetic polyesters under industrial composting: impact on compost properties and phytotoxicity, *Proceedings of ECOpole*, 4 (2010) 133-140
- [119] K. Azim, B. Soudi, S. Boukhari, C. Perissol, S. Roussos, I. T. Alami, Composting parameters and compost quality: a literature review, *Org. Arg.* 8(2018) 141-158. <https://doi.org/10.1007/s13165-017-0180-z>
- [120] T. Ishigaki, W. Sugano, A. Nakanishi, M. Tateda, M. Ike, M. Fujita, The degradability of biodegradable plastics in aerobic and anaerobic waste landfill model reactors, *Chemosphere*, 54 (2004) 225-233. [https://doi.org/10.1016/S0045-6535\(03\)00750-1](https://doi.org/10.1016/S0045-6535(03)00750-1)

- [121] D. Y. Kim, Y. H. Rhee, Biodegradation of microbial and synthetic polyesters by fungi, *Appl. Microbiol. Biotechnol.* 61 (2003) 300-308. <https://doi.org/10.1007/s00253-002-1205-3>
- [122] D. Adamcová, M. D.Vavřková, S. Hermanová, and S. Voběrková, Ecotoxicity of composts containing aliphatic-aromatic copolyesters, *Pol. J. Environ. Stud.* 24 (2015) 1497-505. <https://doi.org/10.15244/pjoes/31227>
- [123] V. Koushal, R. Sharma, M. Sharma, R. Sharma, and V. Sharma, Plastics: issues challenges and remediation, *International Journal of Waste Resources*, 4 (2014) 2-6. <https://doi.org/10.4172/2252-5211.1000134>
- [124] M. A. L. Russo, C. O'Sullivan, B. Rounsefell, P. J. Halley, R. Truss, W. P. Clarke, The anaerobic degradability of thermoplastic starch: Polyvinyl alcohol blends: Potential biodegradable food packaging materials, *Bioresour. Technol.* 100 (2009) 1705–1710. <https://doi.org/10.1016/j.biortech.2008.09.026>
- [125] M. Nitschke, S.G. Costa, and J. Contiero, Rhamnolipids and PHAs: Recent reports on *Pseudomonas*-derived molecules of increasing industrial interest, *Process Biochemistry.* 46 (2011) 621-630. <https://doi.org/10.1016/j.procbio.2010.12.012>
- [126] C. Zhuo, Y. A. Levendis, Upcycling waste plastics into carbon nanomaterials: A review, *J. Appl. Polym. Sci.*, 131(2014) 1-14. <https://doi.org/10.1002/app.39931>
- [127] S. Pandey, M. Karakoti, S. Dhali, N. Karki, B. SantiBhushan, C. Tewari, S. Rana, A. Srivastava, A. B. Melkani, N. G. Sahoo, Bulk synthesis of graphene nanosheets from plastic waste: An invincible method of solid waste management for better tomorrow, *J. Waste Manag.* 88 (2019) 48-55. <https://doi.org/10.1016/j.wasman.2019.03.023>
- [128] L. N. Rao, J. L. Jayanthi, D. Kamalakar, Conversion of waste plastics into alternative fuel, *International journal of engineering sciences & research technology.* (2015) 195-201