

1.1 Introduction

Need for materials have lead to the development and production of a number of synthetic polymers over the past few decades (Pathak *et al.* 2017). Plastics consist of a network of appropriate molecular monomers bound together to form macromolecules. They are economic, energy efficient to produce, light in weight and some are biocompatible as well. More than half a century ago synthetic polymers started to replace natural materials in almost each and every area and rapid growth in their production during 20th century gave rise to the name, “the Century of Polymers” and today plastics have become an crucial part of our life (Thompson *et al.* 2009). Strength and imperishability of plastics have been upgraded constantly with time and hence plastics are now considered as a synonym for substances resistant to many environmental factors. At present, there are more than 20 different major types of plastics in use globally. (APME, 2006). According to a report production and consumption of plastic is growing at an average rate of 9% per year. Over the past 60 years, production has grown from 1.5 million tons in 1950 to 245 million tons in 2008 (Dacko *et al.* 2008). Currently, plastics are almost completely obtained from petrochemicals produced from fossil oil and gas. About 4 per cent of petroleum production is converted directly into plastics every year (British Plastics Federation 2008).Over 300 million metric tons of plastics are produced in the world annually (Halden *et al.* 2010) and about 50% (Souhrada *et al.* 1988) of this volume is for disposable purposes, products that are thrown out within a year of their purchase.

Many plastics materials are derived from natural resources, such as polyolefins from petroleum oil. They have replaced paper and other cellulose-based products for packaging due to their better physical and chemical properties, such as strength,

lightness, inertness to water and most water-borne microorganisms. Almost all facets of everyday life ranging from transport, telecommunications, clothing, footwear and as packaging materials that facilitate the transport of a wide range of food, drink and other goods involve plastics (Devi *et al.*2014).

There is huge potential for newer usages of plastics that will impart betterments in the future, for instance as novel medical practices, in the production of sustainable energy and lowering of energy consumption in transport (Andrady *et al.*2009). Approximately 30% of the plastics have worldwide applications for packaging. This consumption is still increasing at a high rate of 12% per annum (Sabir *et al.*2004).

Plastics which are most widely used in packaging are polyethylene. Almost 64% of all produced plastics are derived from polyethylene (PE). Polyethylene is a polymer resistant to biodegradation. Its high molecular weight and long chain structure cause it unaccessible to micro-organisms and practically impossible as a food source (Hadad *et al.*2005). Its chemical and biological inertness have encouraged its application into numerous products from plastic bags and piping to the construction of fuel storage tanks. Additionally, there is a low level of PE recycling in many countries, and the majority of scrap PEs end up as litter. Therefore, the accumulation rate in the environment is estimated at 25 million tons per year (Soni *et al.* 2009, Zahra *et al.* 2010). India has shown a significant growth in the consumption of plastics and consequent rise in the production of plastic waste. Over 80 million tonnes of polyethylene is manufactured each year making it the most important plastic. This accounts for over 60% of the ethene manufactured each year in India. Packaging is the primary plastic consuming sector, accounting for 42 % of the total consumption, followed by consumer products and the construction industry. The relationship recorded between plastic consumption and the

gross domestic product for several countries is quite often used to estimate future plastic expenditure trend (Ghosh *et al.*2013). Elasticities of the individual material growth in india with respect to GDP were established for the past and for the next three decades assuming a development comparable with that of Western Europe. On this basis, the total plastic consumption is projected to grow by a factor of 6 between 2000 and 2030. Consumption and production of plastic polymer are based normally on demand and supply. In India plastic consumption is estimated as 9.7 kg/person. Fig. 1.1 shows the report generated by Tata strategic on consumption and production of various plastic wastes. It can be clearly seen from this data that consumption and production of polymer has huge gap. Use of plastic product can only be reduced up to certain extent but use of new material for manufacturing can be reduced by using recycling and recovery techniques (Singh *et al.* 2017).

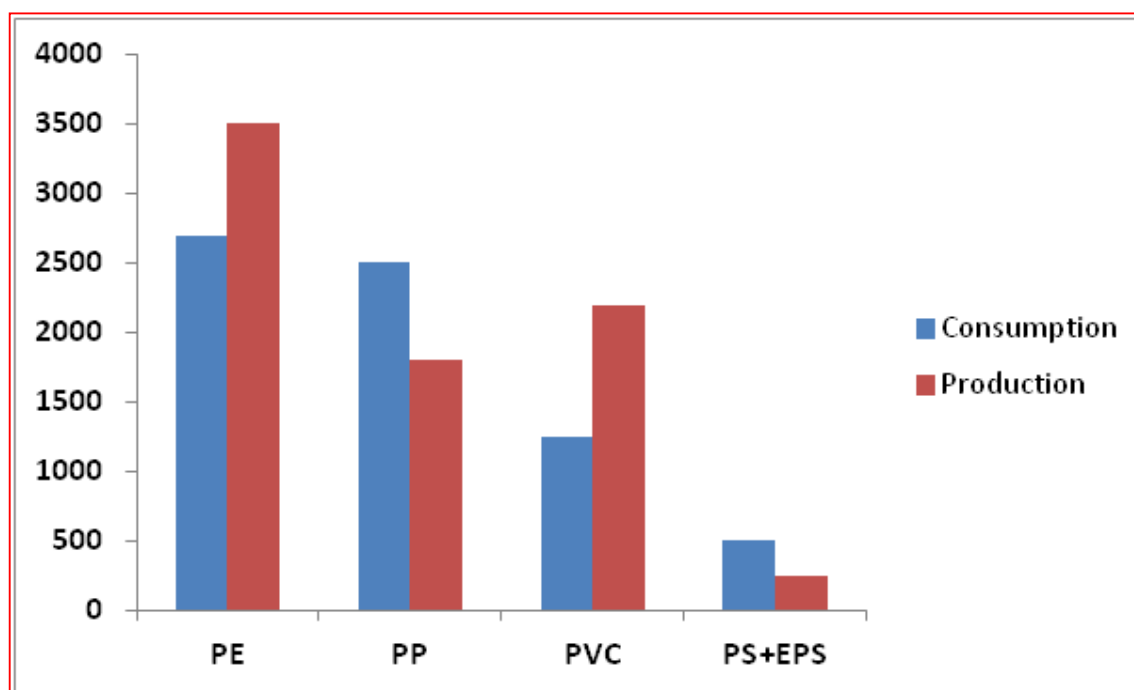


Fig.1.1. Statistics on consumption and production of various plastic materials

(Source: Govt. of India Statistics, Analysis by Tata Strategic)

1.2 Uses of polyethylene

Polyethylene is produced in three main forms: low density polyethylene (LDPE) (density $< 0.930 \text{ g cm}^{-3}$) and linear low density polyethylene (LLDPE) (density $0.915\text{-}0.940 \text{ g cm}^{-3}$) and high density polyethylene (HDPE) (density $0.940\text{-}0.965 \text{ g cm}^{-3}$). Figures 1.2 and 1.3 depict the global consumption of HDPE and LDPE. The LDPE or LLDPE are preferred for film packaging and for electrical insulation. HDPE is blow-moulded to make containers for household chemicals such as washing liquids and drums for industrial packaging. It is also extruded as piping and pipe fittings.

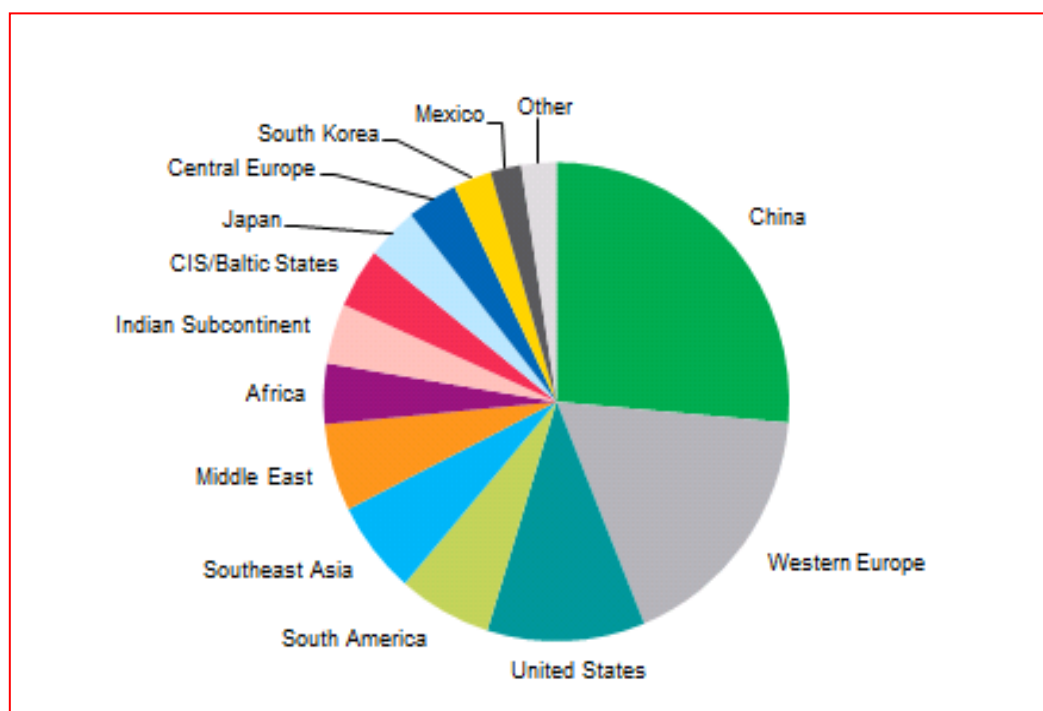


Fig. 1.2 Pie chart showing the world consumption of low density polyethylene (LDPE), 2016

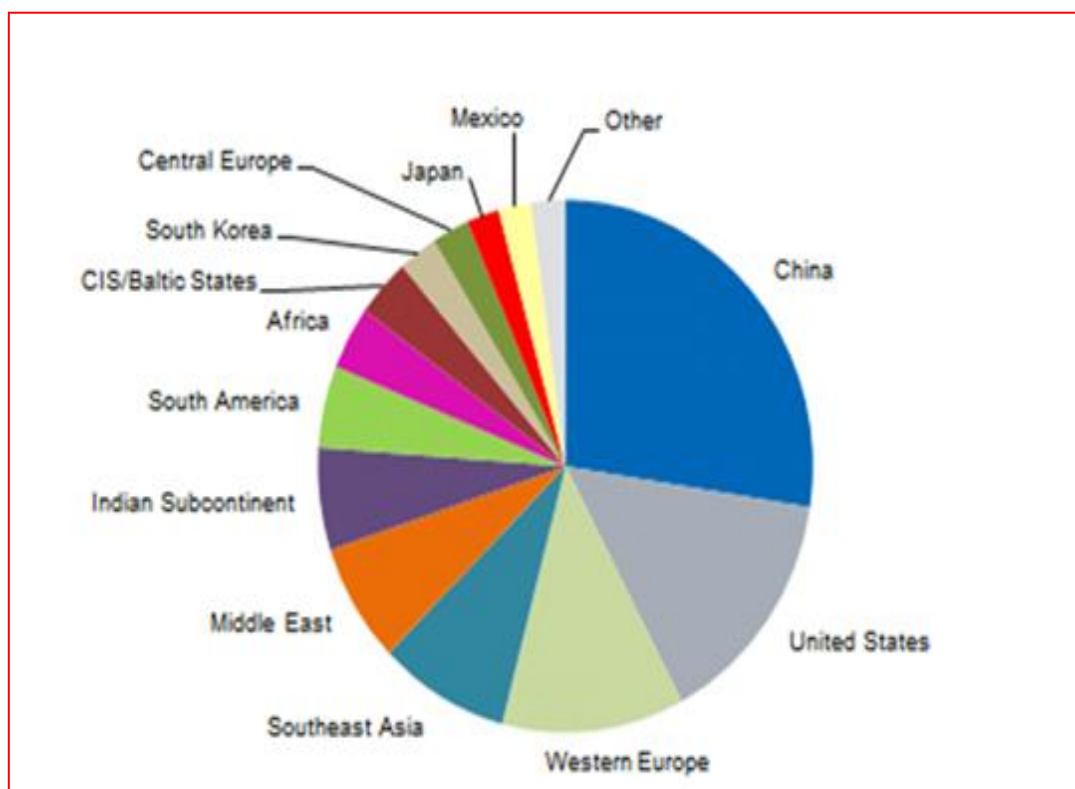


Fig. 1.3 Pie chart showing the world consumption of high density polyethylene (HDPE), 2016

During 2011–16, world polyethylene consumption grew at an average rate of about 3% per year, while the production capacity increased at a slower rate of about 2%, leading to higher utilization rates. Global demand for polyethylene is forecast to grow faster than average world GDP growth rates over the next five years. The most important regions in terms of annual growth are India (~11%) the CIS and Baltic States (8%), the United States (~5.8%), China (~5.6), and the Middle East (~2.5%). These five regions account for 89% of the volume growth between 2016 and 2021. It is seen from figures that in packaging industry mainly LDPE and HDPE are utilized (Fig. 1.4).

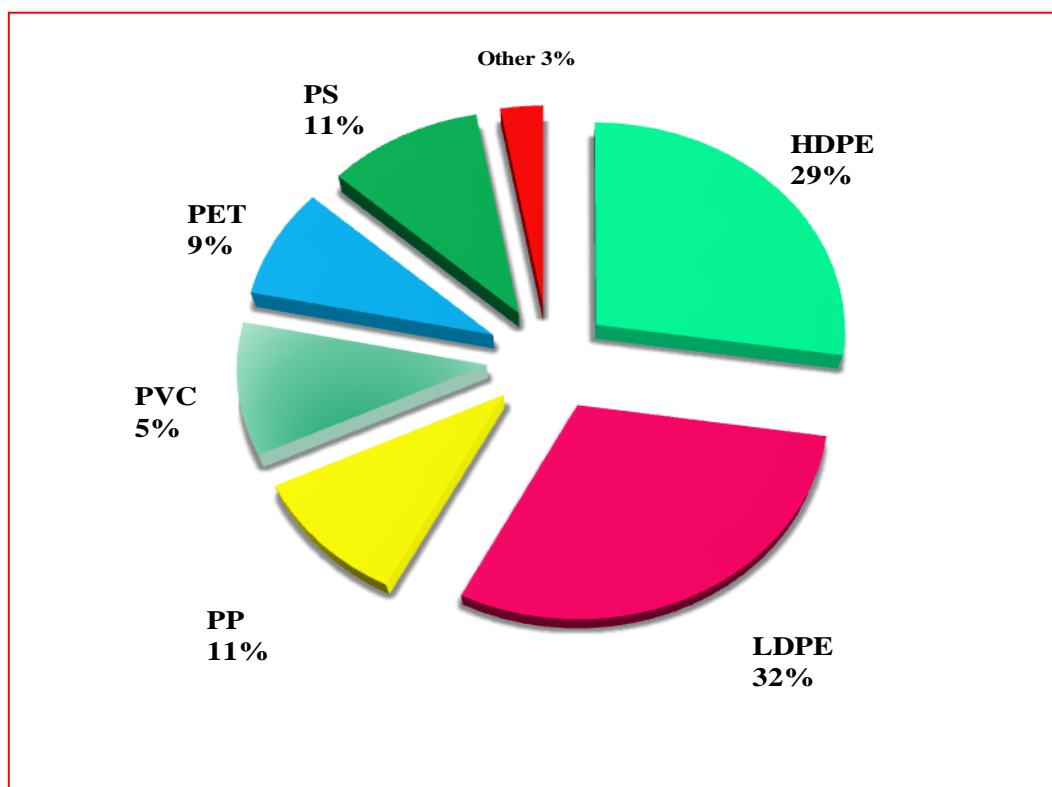


Fig. 1.4 Plastics used for packaging

1.2.1 Low-density polyethylene (LDPE)

It is widely used for manufacturing various containers, dispensing bottles, wash bottles, tubing, plastic bags, and various molded laboratory items. It possesses excellent resistance against dilute and concentrated acids, alcohols, bases and esters, and accumulates at a rate of 25 million tons per year (Orhan and Buyukgungor, 2000). It should be noted that low-density polyethylene (mainly used as carry bags) constitutes the major portion of this waste problem (Harshvardhan *et al.* 2013). In spite of this the global need for LDPE is sharply increasing and however, an accumulation of waste LDPE products in the environment is adversely affecting the ecosystem. In its original form polyethylene is not biodegradable. The increasing levels of LDPE waste; decreasing landfill capacity and very slow rate of LDPE degradation in the environment have aroused the interest of researchers in its biodegradation.

1.2.2 High-density polyethylene (HDPE)

It is a thermoplastic synthesized from ethylene by a catalytic process. It has little branching, resulting in stronger intermolecular forces and tensile strength (4550 psi approx.) greater than low-density polyethylene (LDPE). Generally, it is believed that higher the density greater the stability because of shortened bond length and tight packaging. Physically, HDPE is harder, more opaque and can withstand somewhat higher temperatures (120°C). HDPE is also used in many products and packaging such as carry bags, milk jugs, detergent bottles, margarine tubs, garbage containers and water pipes. Thus, it has wide industrial and day-to-day applications. The extensive usage of HDPE poses severe environmental threats to terrestrial and marine ecosystem, as they are hardly degradable and voluminously dumped after usage.

1.3 Pollution due to Polyethylene

1.3.1 Terrestrial environment

Almost all types of terrestrial ecosystems like deserts (Zylstra, 2013), forest, grasslands (Gregory *et al.* 2009) and polar regions (Nuttall 2000, Lytle 2015) are affected by polythene pollution. In United Arab Emirates camel and endangered desert animals are reported dead by eating polythene bags along with the food (Terry 2015). There had been a case where a platypus suffered deep wounds in body when a plastic bag twisted around its body (McNamee 2009). Even delicate flora and fauna of tundra is not safe from polythene pollution due to increased human interference (Hu *et al.* 2014).

1.3.2 Aquatic environment

Polyethylene is not only harmful to terrestrial flora and fauna; it has also been known to have a calamitous effect on aquatic environment (Browne *et al.* 2011). Not only

Oceans are polluted but seabed near the coastal areas is also found to be contaminated by plastic bags. The menace to marine environment is caused by debris of plastics (Webb *et al.* 2013). These debris lead a drastic reduction in marine fauna population, either they entangled through their body or they are ingested by fishes and birds mistaking the debris to be a prey (Derraik *et al.* 2002). According to Greenpeace report (2006) around 80% of marine debris is from land and remaining 20% is from other water bodies. Major sources of marine debris are tourist activities at sea beaches, debris from sewer, fishing material (Corcoran *et al.* 2009) and wastes from boats and ships (Denuncio *et al.* 2011). However, those plastics which are degraded either mechanically or chemically are ultimately reduced to tiny pieces of the size of grains. These tiny particles are then ingested by various small creatures and may concentrate as persistent organic pollutants (POPs) present in seas. Marine debris has affected 267 species globally out of which, 86% are sea turtles, 44% seabird species and 43% marine mammal species (Browne *et al.* 2011).

1.4 Polyethylene disposal methods

There is an urgent requirement to find out the appropriate methods for polythene disposal. Four possible approaches viz. thermal treatment, land filling, recycling and biodegradation can be used for managing plastic wastes (Fig.1.5). All methods have their inherent limitations.

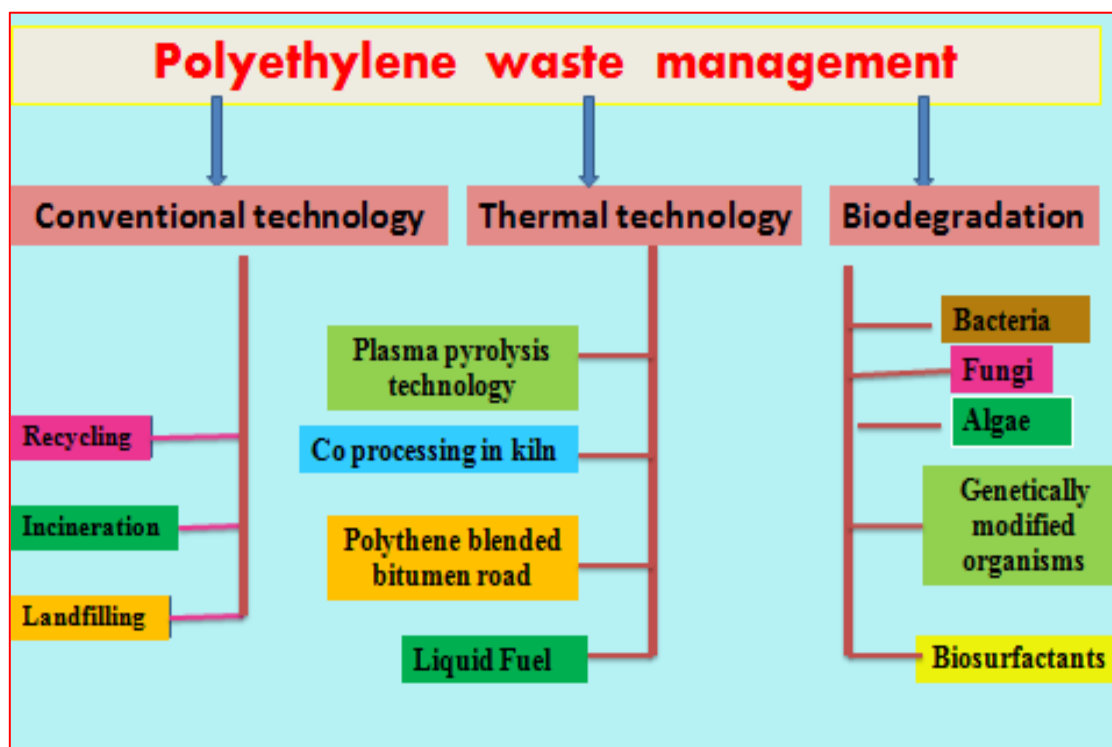


Fig.1. 5 methods of Polyethylene waste management

1.4.1 Conventional techniques

1.4.1.1 Recycling

Recycling of plastics involve many processes including mechanical, chemical and thermal depolymerisation. Recycling of a wider range of post-consumer plastic packaging will enable improvement in recovery rates of plastic waste and diversion from landfills (Hopewell *et al.* 2009) .These include four categories: primary (mechanical reprocessing into a product with equivalent properties), secondary (mechanical reprocessing into products requiring lower properties), tertiary (recovery of chemical constituents) and quaternary (recovery of energy). (Hopewell *et al.* 2009, Salem *et al.* 2017, Fisher *et al.* 2003) (Table1.1).Primary recycling is often referred to as closed-loop recycling, and secondary recycling as downgrading. Tertiary recycling is either described as chemical or feedstock recycling and applies when the polymer is de-polymerized to its chemical

constituents (Fisher *et al.* 2003). Quaternary recycling is recovery of energy, energy from waste or valorization. LPDE can be recycled to form products like plastic lumber, trash bags, etc. Chemical recycling recovers the petrochemical constituents of the polymer, which can then be used to re-manufacture plastic or to make other synthetic chemicals. These recycling methods are not cost effective (Patel *et al.* 2000). It has been concluded by several researchers that during recycling more toxic and larger amounts of hazardous volatile organic compounds are emitted from melted virgin and waste plastic pellets than producing virgin plastics (Yamashita *et al.* 2009, He *et al.* 2015).

Only 1% of total plastic waste generated in india is recycled as it is a costly process and rest is dumped in dumping grounds (Central Pollution Control Board 2013). The recycled plastics have proved to be more hazardous than virgin plastic as during recycling a number of harmful colours, additives, stabilizers etc are mixed. Also plastics cannot be recycled more than 3 times as each recycling results in decrease in its strength. At dumping grounds, it takes approximately 300 years for a plastic to naturally degrade in environment (Central Pollution Control Board 2013). In addition to this, plastics degraded by photo degradation into very small toxic parts which ultimately contaminate soil, water bodies and hence animals and humans consuming them (Corcoran *et al.* 2009). Non-recyclable plastic wastes (e.g. thermostat plastic, multilayer plastics etc) cause disposal problems (Lee *et al.* 1991). Polyethylene wastes are recycled to produce plastic cement (Jassim *et al.* 2017). Chemical recycling followed by pyrolysis results in a series of hydrocarbons (alkanes and alkenes), with a great potential to be recycled back into the petrochemical industry as a feedstock for the production of new plastics or refined fuels (Achilias *et al.* 2007).

Plastic bags are recycled not because of their recyclable qualities but because of their manufacturing process, which uses around 70 percent less energy and releases 50 percent fewer greenhouse gases than alternatives like paper bags.

Table 1.1 Terminology used in different types of plastics recycling and recovery

ASTM D5033 definitions	Equivalent ISO 15270 (draft) definitions	other equivalent terms
Primary recycling	Mechanical recycling	Closed-loop recycling
Secondary recycling	Mechanical recycling	Downgrading
Tertiary recycling	Chemical recycling	Feedstock recycling
Quaternary recycling	Energy recovery	Valorization

1.4.1.2 Landfilling

When polyethylene are dumped in a field or in dumping areas, there is evidential proof that they cause a great change in the pH of the soil followed by disturbance in the leaching of the rain water and moisture, making the land bare and unfertile. The biological degradation time of PE is very high, and it takes thousands of years to degrade these long chain polymers into simple hydrocarbons (Ghosh *et al.*2013). Latest reports confirm that some plastic products are mimicking human hormones (e.g., thyroxin and sex hormones), causing human health hazards (Soto *et al.* 1991, Hao *et al.* 2011). Polythene debris remain for very long time in landfill and it has been published in a report that it will take around 1000 year to breakdown in landfills (Lapidos *et al.*2007) and leaving the land barren Landfilling has its own associated limitations as it requires a vast amount of space which remains unavailable for a very long time (Webb *et al.* 2013). Degradation rate of polythene is very slow in landfills due to anaerobic environment (Grover *et al.* 2015). Secondary environmental pollution is a major problem of landfills. Pollutants are released in the form of leachates as well as gases viz. toluene, benzene,

xylene ethyl and trimethyl benzene. In addition to these chemicals other estrogenic compounds include bisphenol A (BPA), phthalate and PBB (polybrominated biphenyls) (Xu *et al.* 2011). These compounds are very harmful to human health causing diseases related to reproductive system of mammals and different types of cancer like prostate, ovarian and breast cancer (Yang *et al.* 2011).

1.4.2 Thermal techniques

1.4.2.1 Incineration

It is the energy recovery through complete oxidation. Incinerating solid waste serves two purposes in the advanced waste management system. Primarily, it reduces the amount of waste for sanitary landfilling; and uses waste for energy production (power or heating). Hence, waste incineration plants are generally introduced in areas where the siting of sanitary landfills is in conflict with other interests such as city development, agriculture, and tourism (<http://web.mit.edu/urbanupgrading/urbanenvironment/resources/references/pdfs/MunicipalSWIncin.pdf>). Thermal treatment of polyethylene results in release of harmful gases during fires or waste burning like carbon monoxide, chlorine, furans, dioxins, CCl₄, etc resulting into breathing problems (Nisar *et al.* 2011). The final products of incineration are ash and exhaust gases. It has been estimated that the carbon footprint of LDPE or polyethylene is about 6 kg CO₂ per kg of plastic (Juerg 2015). These exhaust gases contain highly toxic products: PAHs, dioxins and furans which cause severe air pollution.

1.4.2.2 Pyrolysis

Pyrolysis is the thermal degradation of carbonaceous materials. It is a versatile method which can produce a range of useful hydrocarbons potentially used as a chemical

feedstock or as energy. This could minimize the dependency on non-renewable fossil fuels and in addition solve the landfilling problem. Pyrolysis has environmental advantages compared to other PSW treatment methods as it takes place in an atmosphere free of oxygen, thus does not produce dioxins and has reduced carbon monoxide and dioxide emissions. Many investigators have studied the pyrolysis of polyethylene (Mangesh *et al.* 2017, Sonawane *et al.* 2016, Obeid *et al.* 2014, Zeaiter *et al.* 2014, Kumar *et al.* 2013, Lee *et al.* 2012, Westerhout *et al.* 1997, Bockhorn *et al.* 1999). It is a flexible process as the conditions such as temperature, pressure and residence time can be easily varied to achieve the desired product distribution. Catalytic pyrolysis has several advantages over the thermal process, as it improves efficiency by decreasing the process's residence time and affects the product selectivity. Moreover, catalytic cracking using the catalysts such as zeolites results in high quality products in the range of motor engine fuels, therefore reducing the need for any further upgrade downstream of pyrolysis processes. The catalysts are expensive and the design has to consider the possibility of avoiding catalyst poisoning and deactivation by the impurities in the feedstock. (Salem *et al.* 2017).

1.4.2.3 Plasma Pyrolysis

It is an effective method to destroy polyethylene in an eco-friendly manner. This method uses a plasma torch in oxygen deprived environment at very high temperature (usually between 325 - 850°C). The temperature variations during pyrolysis cause different gases production. Thus, at low temperature, usually the gases produced are found to be carbon dioxide, ethylene, propylene, carbon monoxide, butadiene and methane, whereas, at high temperature along with carbon dioxide, carbon monoxide and

ethylene, some additional gases produced are benzene, methane and hydrogen (Ademiluyi *et al.* 2007).

1.4.2.4 Co-processing in kiln

Co-processing refers to the use of waste polyethylene in industrial processes such as cement and power stations or any other large combustion plants. Co-processing involves substitution of primary fuel and raw material by waste. Waste material such as PE waste used for co-processing are referred to as alternative fuels and raw material (AFR). Co-processing of plastic waste offers advantages for cement industry as well as for the Municipal Authorities responsible for waste management. On the other hand, cement producers or power plants can save fossil fuel and raw material consumption, contributing to more eco-efficient production. In addition, one of the advantage of the recovery method in the existing facility is eliminating the need to invest in other plastic waste management practices and secure land filling. (Overview of the plastic waste management, CPCB Report, 2013)

1.4.2.5 Polyethylene blended bitumen road

The studies on the thermal behavior and binding property promoted a study on the preparation of polythene carry bags-bitumen blend and its properties to find the suitability of the blend for road construction (Appiah *et al.* 2017, Sreejith, 2010). The polyethylene coated aggregate bitumen mix and polyethylene modified bitumen forms better materials for flexible pavement construction as the mixes shows higher Marshall Stability value and suitable Marshall Coefficient. Hence the use of waste polyethylene for flexible pavement is one of the best methods of easy disposal of waste polyethylene. The use of polyethylene coated aggregate is better than the use of polyethylene modified bitumen in many aspects. For example if all the roads in India (3.3 million km) are converted into

plastic tar road, all the waste plastic available will be used on the road and the disposal of waste plastics will no longer be a problem. But as melting and mixing plastic waste with bitumen causing health hazards and also air pollution, thus it should be restricted to open areas or in lesser populated areas. Also; the workers involved should be provided with proper safety devices.

1.4.2.6 Liquid fuel

High temperature pyrolysis and cracking of waste polyethylene are environmentally accepted methods for their utilization. It is a typical chemical recycling process enabling production of monomers (ethylene) or liquid hydrocarbons (Refuse derived fuel). The cracking of polyethylene, in its monomeric forms is well described in literature (Panda *et al.* 2010, Lee *et al.* 2002, Park *et al.* 2002 Serrano *et al.* 2000, Miranda *et al.* 2002, Grieken *et al.* 2001, Karaduman *et al.* 2002 & Faravelli *et al.* 2003).

1.5 Biodegradation of Polyethylene

Biodegradation is defined as any physical or chemical change in a material caused by biological activity. Microorganisms such as bacteria, fungi and *actinomycetes* are involved in the degradation of both natural and synthetic plastics. Plastics are usually biodegraded aerobically in nature, anaerobically in sediments and landfills and partly aerobically in compost and soil. Carbon dioxide and water are produced during aerobic biodegradation, (Seymour *et al.* 1989) while anaerobic biodegradation produces carbon dioxide, water and methane (Datta *et al.* 1998). This process may also be termed as reverse flow to produce simple hydrocarbons because these polymers are usually produced from different petrochemical products. Thus it is possible to go back to simple monomers which can be an alternative source of energy and may even be the next generation fuel. Recent research suggests that there are several microorganisms

(especially some bacteria and fungi) which have the capacity to degrade these synthetic polymers in a much faster way in comparison to the natural method by using some exoenzymes under stress conditions. In view of the currently focus has shifted to biodegrade the plastic with the help of various microorganisms and recover value from polythene (David *et al.* 2009, Sharma *et al.* 2013, Singh *et al.* 2005). In biodegradation of polythene, strong carbon bonds are broken down through microbial actions that reduces the strength of polythene (as molecular weight decreases) and hence polythene gets degraded (Pruter *et al.* 1987).

1.5.1 Polythene degrading enzyme

Two types of enzymes are involved in biodegradation of polyethylenes: intracellular and extracellular depolymerases. During degradation the exoenzymes or the extracellular depolymerases from the microorganisms convert the long chained polyethylene into molecules having shorter chains (Moser *et al.* 1992, Azzarello *et al.* 1987). These molecules are monomers, dimers or oligomers that are small enough to pass through the semi permeable bacterial cell membrane. These are then utilised by the bacteria as sources of carbon and energy. This process is termed as depolymerisation. The process in which the end products are water, carbon dioxide or methane, is called mineralization. The presence of CH₂ group in polythene structure as the only group, makes polythene surface hydrophobic (Sangale *et al.* 2012). These surfaces are made hydrophilic by initial degradation, resulting in insertion of hydrophilic groups. Degradation of polythene occurs in 2 steps namely, primary degradation and ultimate degradation. After degradation polythene is converted to low molecular weight dimers or monomers due to the cleavage of the main chain (Laist *et al.* 1997). Polythene degradation pathway is quite similar to the degradation pathway followed by ligninolytic fungi. In

ligninolytic fungi like mushrooms and lignin degrading bacteria, extracellular enzymes consist of oxidases, laccases and peroxidases which results in production of extracellular hydrogen peroxide. Thus primary degradation results in production of CH₄, CO₂ and H₂O.

1.5.2 Mechanism of Enzymatic Biodegradation

The primary mechanism for the biodegradation of high molecular weight polymer is the oxidation or hydrolysis by enzyme to create functional groups that improves its hydrophilicity. Consequently, the main chains of polymer are degraded resulting in polymer of low molecular weight and feeble mechanical properties, thus, making it more accessible for further microbial assimilation (Albertsson and Karlsson 1990, Albertsson *et al.* 1987, Huang *et al.* 1990).

Enzymatic biodegradation is the most attractive method for polyethylene waste treatment. Polyethylene degradation through microbial enzymes comprises two steps. Firstly enzyme adheres to the polyethylene substrate and then catalyzes a hydrolytic cleavage. Intracellular and extracellular depolymerases in fungi and bacteria degrade the polyethylene. Endogenous carbon content is hydrolyzed by intracellular degradation while the utilization of exogenous carbon source is through extracellular degradation (Tokiwa *et al.* 2004). Polyethylene disintegrates into short chains of oligomers, dimers, and monomers which pass through the bacterial membranes and act as a source of carbon and energy. This process is referred as depolymerisation and mineralization is the degradation process in which the end products are carbon dioxide (CO₂), water (H₂O) or methane (CH₄) (Frazer *et al.* 1994). Temperature, pressure and moisture are the physical parameters which chemically and mechanically damage the polyethylenes due to which the

biological forces like enzymes and other metabolites produced by microbes induce the process (Yang *et al.* 2014). The mechanism of the biodegradation of plastics can be easily represented by the following flowchart (Fig1.6).

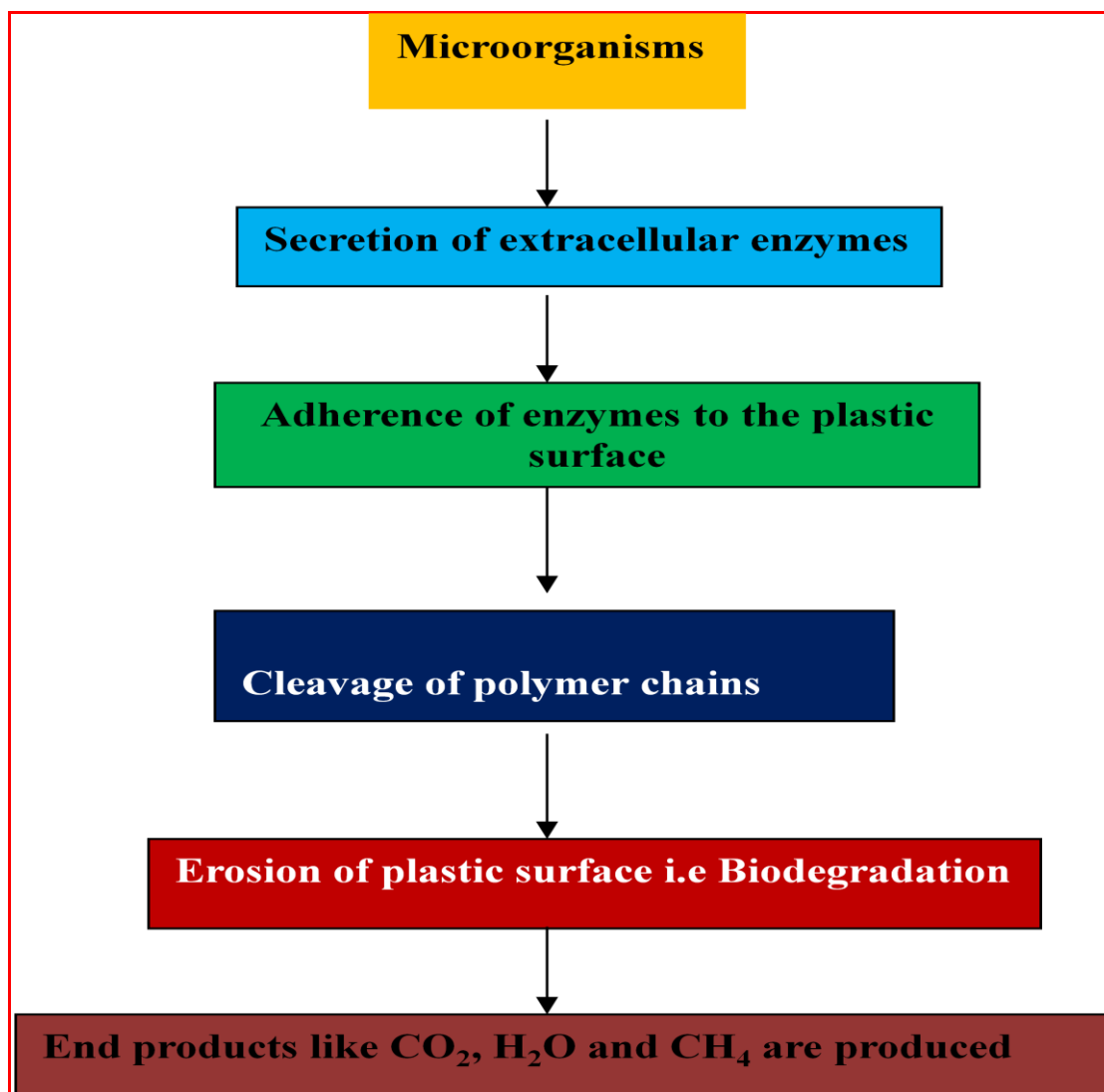


Fig. 1.6 Mechanism of Enzymatic Biodegradation of Plastics (Shah *et al.* 2008)

1.5.3 Factors Affecting Biodegradation of Polyethylene

Biodegradation of Polyethylene by bacteria and fungi proceeds differently under different soil conditions according to their properties. The different factors that govern biodegradation are type of organism, polythene characteristics and nature of pre-treatment. Polythene characteristics refer to its tacticity, mobility, crystallinity, molecular

weight, the type of functional groups and other substituents present in its structure and additives or plasticizers added to it (Kasirajan *et al.* 2012). It was observed that Biological degradability of polyethylene by microorganisms decreases with increase in the molecular weight. With increase in molecular weight, there is decrease in the solubility which makes it unfavourable for microbial attack as it needs to be assimilated into the bacterial cell membrane and broken down by cellular enzymes. Repeating units of polymers like monomers, dimers and oligomers are easily degraded and mineralised (Shah *et al.* 2008). Biodegradation is enhanced by abiotic hydrolysis, photo-oxidation and physical disintegration. These processes enhance the surface area of the polymer and reduce its molecular weight; facilitating microbial degradation (Kasirajan *et al.* 2012). Amorphous regions are more susceptible to microbial degradation than crystalline regions (Restrepo *et al.* 2014). The presence of a glucose source reduces the rate of biodegradation as glucose is a more preferred carbon source than plastic (Muthukumar *et al.* 2015).

1.5.4 Efficiency of Biodegradation

High hydrophobic nature and molecular weight of PE prevent their degradation by microorganisms. However, some microorganisms are capable of breaking down polyolefin of low molecular weight after photo degradation and chemical treatment. To make polyolefin susceptible to microbial degradation, their chain length and molecular weight must be reduced and their hydrophilic level must be improved by oxidation. Polyethylene can be made susceptible to microbial degradation by oxidation with light or heat treatment. It improves the hydrophilic nature of polyethylene so that it can be catalysed by microbial enzymes. Microorganisms can easily degrade this part (Shah *et al.* 2008).

With majority of treatment techniques having major drawback of generation of another type of wastes, biodegradation appeared to be very promising techniques. Bioremediation is proved to be not only a cost-effective technique; it also leads to the complete mineralization of the organic pollutants and generates nontoxic end-products. It is undoubtedly a sustainable and economically feasible technique for the remediation of environmental pollutants. It has also proved to be a successful process in the laboratory and also in many cases, in the natural environment. Several *in-situ* and *ex-situ* bioremediation processes are operational at contaminated sites around the globe.