

**BIODEGRADABILITY STUDIES OF LINEAR LOW DENSITY
POLYETHYLENE AND ITS BLENDS USING COMPOSTED
MUNICIPAL SOLID WASTE**

*A Thesis report submitted in partial fulfillment of the requirements for
the award of degree of*

Master of Technology

In

Chemical Engineering

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CERTIFICATE

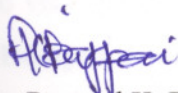
This is certified that the thesis entitled “**Biodegradability Studies of Linear Low Density Polyethylene and its Blends using Composted Municipal Solid Waste**”, is an authentic record of my own work carried out as requirements for the award of degree of M.Tech (Chemical Engineering) at Thapar University, Patiala, under the guidance of Dr. Pramod K. Bajpai (Distinguished Professor, ChED) and Dr. Haripada Bhunia (Assistant Professor, ChED) during January to July 2011.

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It is certified that the above statement made by the student is correct to the best of our knowledge and belief.





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ABSTRACT

Biodegradation of polymers is a promising method for solving various environmental issues. Present study illustrates the biodegradation of linear low density polyethylene (LLDPE) and its blends using municipal solid waste compost under controlled composting conditions according to modified ASTM D 5338 (2003). Composting of samples was carried out for a period of 45 days and the resulting samples were checked for the biodegradation by weight loss, spectroscopic analysis as well as by the protein concentration estimation. Percent weight loss of samples after degradation was found to be as high as 5.72%. Microbial biomass present on the polymer films revealed increases in protein concentration which proves the formation of biofilm on the samples. Spectroscopic analysis was carried out by Fourier Transform Infrared Spectroscopy which revealed the formation of as well as disappearance of various functional groups clearly showing the extent of biodegradation caused by various microorganisms present in the compost. The possible reason of observed changes was also discussed. All these observations confirmed that significant degradation of polyethylene and its blends occurred by composting method.

TABLE OF CONTENTS

Item No.	Page No.
Certificate.....	ii
Acknowledgements.....	iii
Abstract.....	iv
Table of Contents.....	v
List of Figures.....	vii
List of Tables.....	viii
List of Abbreviations.....	ix
Chapter 1: INTRODUCTION.....	1
Chapter 2: LITERATURE REVIEW.....	6
Chapter 3: MATERIALS & METHODS.....	13
3.1 Materials.....	13
3.1.1 Plastic films.....	13
3.1.2 Compost.....	13
3.2 Methodolgy.....	14
3.2.1 Pretreatment of polymers.....	14
3.2.2 ASTM D5338 (2003) Standard.....	14
3.2.3 Controlled Composting (Modified ASTM D5338(2003)).....	15

3.3 Analytical/ Testing procedures.....	15
3.3.1 Determination of dry weight of residual polymers.....	15
3.3.2 Fourier transform infrared (FTIR) spectroscopy.....	16
3.3.3 Estimation of bacterial biomass colonizing the polymers.....	16
Chapter 4: RESULTS & DISCUSSIONS.....	18
4.1 Percentage weight loss.....	18
4.2 Protein estimation.....	20
4.3 Fourier transform infra-red (FTIR) spectroscopy.....	21
Chapter 5: CONCLUSIONS & FUTURE PROSPECTS.....	27
5.1 Conclusions.....	27
5.2 Future prospects.....	28
 REFERENCES.....	 29
 PUBLICATIONS.....	 34

LIST OF FIGURES

Figure 1.1	Overview of degradation of polymers
Figure 1.2	General mechanism of polymer biodegradation.....
Figure 4.1	Percentage weight loss after composting.....
Figure 4.2	Comparison of protein conc. in LLDPE and its blends.....
Figure 4.3	FTIR spectra of LLDPE before composting.....
Figure 4.4	FTIR spectra of LLDPE after composting.....
Figure 4.5	FTIR spectra of LLDPE 80/20 before composting.....
Figure 4.6	FTIR spectra of LLDPE 80/20 after composting.....
Figure 4.7	FTIR spectra of LLDPE 80/20/4 before composting.....
Figure 4.8	FTIR spectra of LLDPE 80/20/4 after composting.....
Figure 4.9	FTIR spectra of Biodegradable polymer before composting.....
Figure 4.10	FTIR spectra of Biodegradable polymer after composting.....

LIST OF TABLES

Table 4.1	Percentage weight loss of plastic films under compost.....
Table 4.2	Estimation of protein concentration.....

LIST OF ABBREVIATIONS

ASTM	American Society for Testing and Materials
ATR	Attenuated Total Reflectance
BSA	Bovine Serum Albumin
CA	Cellulose Acetate
EDPs	Environmentally Degradable Polymers
FTIR	Fourier Transform Infra-Red Spectroscopy
ISO	International Organization for Standardisation
LDPE	Low Density Polyethylene
LLDPE	Linear Low Density Polyethylene
OD	Optical Density
OMMT	Organophillic Montmorillonite
OPE	Oxo-biodegradable Polyethylene
OPENac	Oxo-biodegradable Polyethylene Nanocomposite
PBS	Polybutylene Succinate
PBSA	Poly(Butylene Succinate-Co-Adipate)
PCL	Polycaprolactone
PE	Polyethylene
PHBV	Poly(3-hydroxybutyrate-co-3-hydroxyvalerate)

PLLA	Poly(L-Lactic Acid)
PP	Polypropylene
PP-TT	Thermally Pretreated Polypropylene
PP-UT	Unpretreated Polypropylene.
PVA	Polyvinyl Alcohol
SEM	Scanning Electron Microscopy
SPVA	Starch and Polyvinyl Alcohol
TDPA	Thermally degradable low density Polyethylene
TPDAS	Thermoplastic Di-Aldehyde Starch
TPS	Thermoplastic Starch
TS	Total Solids
VS	Volatile Solids

Chapter 1

INTRODUCTION

Plastics are man-made long chain polymeric molecules (Zheng et al., 2005). More than a half century ago polymers started to substitute natural materials in almost all areas and now plastics have become an indispensable part of our life. With time, stability and durability of these compounds have improved continuously. These are extensively used in packaging of food products, pharmaceuticals, cosmetics etc. They have replaced paper and other cellulose based products for packaging because of their better physical and chemical properties. Production of these polymer compounds has shown dramatic increase during past few years.

Polymeric materials are complex molecular structures constituted by large chains containing thousands of little units called monomers. These are chemical compounds with high molecular weight consisting of a number of structural units linked together by covalent bonds (Kyrikou et al., 2007). In most cases they are organic compounds based on carbon, although there are others based on inorganic substances.

Though, there are several types of polymers, they are classified under two major categories namely:

Natural polymers: Polymers are widely found in nature. Carbohydrates are naturally occurring organic compounds that are related to simple sugars (Baistoli, 2005). Cellulose, another natural polymer, is the main structural component of plants.

Synthetic polymers: Synthetic polymers are often referred to as "plastics". However, most of them can be classified in at least two main categories: thermoplastics and thermosets.

- *Thermoplastics:* Most polymers are formed into the desired shapes after softening or melting by heating. In thermoplastics, the atoms and molecules are joined end-to-end into a series of long, sole carbon chains. These long carbon chains are independent of the others (Allen *et al.*, 1999).
- *Thermosets:* Polymers which lose their structural integrity upon melting by heating are called thermosets. Distinguished from the linear structure of thermoplastics, thermoset

plastics have a highly crosslinked structure (Alauddin *et al.*, Scott, 1999). Examples include Bakelite and vulcanized rubber (Zheng *et al.*, 2005).

Synthetic polymers are used extensively in various fields due to their durability and stability. During the past 3-decades, plastic materials have been increasingly used in food, clothing, shelter, transportation, construction, medical and recreation industries. Plastics are advantageous as they are strong, light-weight, inexpensive, easily processable, and durable. However, they are disadvantageous as they are resistant to biodegradation, leading to pollution, harmful to the natural environment. Fluorinated polymers have become a great danger in the environment and are thought to cause cancer in man. Their ubiquitous presence is seen in microwave popcorn bags, stain-free carpets, fast-food wrappers, windshield washer fluid. Because of their durability and visibility in litter, plastics (polymers) have attracted more public and media attention than any other component of the solid waste stream. The plastic waste stream emerges from domestic, industrial and municipal refuse (Jayasekara *et al.*, 2005). Thus, improperly disposed plastic materials are a significant source of environmental pollution, potentially harming life.

The three main strategies available for the management of plastic waste are incineration, recycling and landfill (Ammas *et al.*, 1998). These strategies are not optimal and remain the subject of much controversy and discussion among both scientists and the public.

Degradation of plastics refers to any physical or chemical change in the polymers as a result of environmental factors, such as light, heat, moisture, chemical conditions or biological activity. Several methods of degradation have been developed during past few years to convert the polymeric long chain molecules into simpler ones so that their disposal is environment friendly and safe. Moreover, degraded polymers are helpful for recycling. Various methods of degradation are illustrated briefly in figure 1.1.

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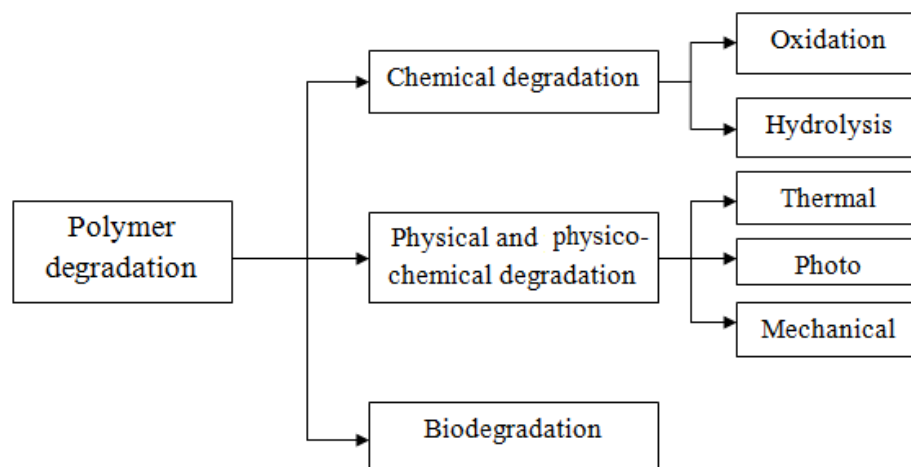


Fig 1.1 Overview of the methods of degradation of polymers

Indeed, biodegradation is an efficient and rapid way for eliminating some plastic wastes under composting and landfilling conditions [Massardier-Nageotte *et al*, 2006]. It is likely that biodegradable plastics may simply become part of a natural cycle.

Biodegradation is the ability of microorganisms to influence abiotic degradation through physical, chemical or enzymatic action (Chilleni *et al.*, 2003). The term is often used in relation to ecology, waste management, environmental remediation and to plastic materials, due to their long life span (Shah *et al.*, 2008).

Polymeric materials are not easily biodegraded. Efforts have been directed to develop mild physiochemical processes which includes thermal and radiation pretreatments to enhance biodegradation process (Sudhakar *et al.*, 2007).

Microorganisms such as bacteria and fungi are involved in the degradation of both natural and synthetic plastics. The biotic mechanism reported for degradation of high molecular weight polymers are due to extra cellular enzymes produced by microorganisms which degrade the main polymeric chain and results in intermediates of lower molecular wt. with modified mechanical properties, making it more accessible to microbial degradation. Two categories of enzymes are actively involved in biological degradation of polymers: extracellular and intracellular depolymerases. During degradation, exoenzymes from microorganisms breakdown complex

polymers yielding smaller molecules of short chain, e.g. oligomers, dimers, and monomers, that are small enough to pass the semi-permeable membrane, and then can be utilized as carbon and energy sources. The process is called depolymerisation. When the end products are CO_2 , H_2O , CH_4 , the degradation is called mineralization. Small portion of polymer is incorporated inside the microbial biomass, humus and other natural products, so the polymer degradation rarely reaches 100%. General mechanism of plastic biodegradation is depicted in figure 1.2

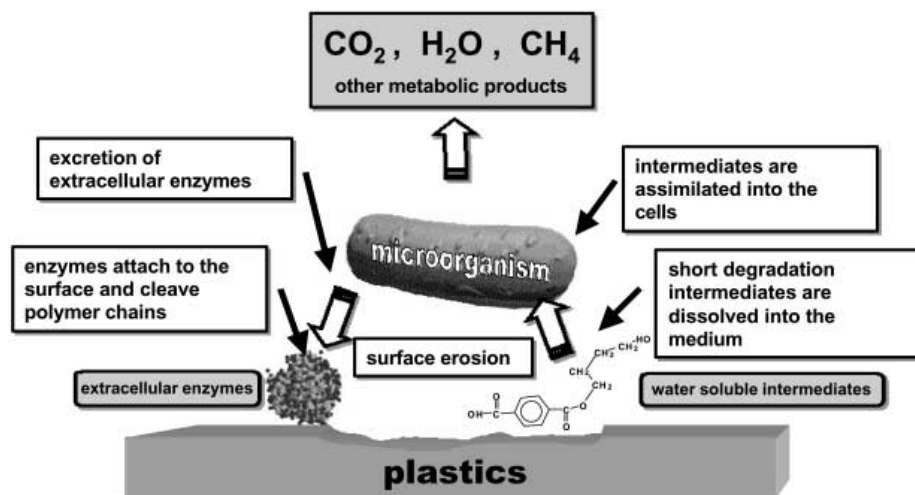


Fig. 1.2 General mechanism of polymer biodegradation

Biodegradation of plastics proceed actively under different soil conditions according to their properties, because the microorganisms responsible for the degradation differ from each other and they have their optimal growth conditions in the soil. Due to similar material properties as conventional plastics, the biodegradable plastics have been developed successfully over past few years (Zheng et al., 2005).

Biodegradable plastics, as novel materials claim to be environmentally friendly. The number of different environments in which the plastic may be degraded have made necessary the establishment of a complex and extensive battery of test methods and evaluation criteria for these materials.

The development of environmentally degradable polymers (EDPs) was initiated among several other attempts in the early 1980s to address an emerging global plastic waste problem, following decades of fast development and explosive growth of plastic utilization (Scott, 1999).

Environmentally degradable polymeric materials and plastics (EDPs) comprise new kinds of plastic items, which are designed to exhibit a significant degradation resulting in environmentally compatible end products, namely CO₂, water, and cell biomass within an acceptable time frame [Krzan *et al.*, 2006].

The successful production and marketing of biodegradable plastics will help alleviate the problem of environmental pollution. In the past 10 years, several biodegradable plastics have been introduced into the market. However, none of them is efficiently biodegradable in landfills. For this reason, none of the products has gained widespread use (Anonymous 1999). Hence, there is an urgent need to develop biodegradable polymers and efficient microbial system to solve this global issue.

Chapter 2

LITERATURE REVIEW

With the advances in technology and the increase in the global population, polymers have found wide applications in every aspect of life and industries (Tokiwa *et al.*, 2009). According to recent investigation on discarded plastics approximately 738 plastic bags are discarded per person per year. Polypropylene (PP) and polyethylene (PE), expressed as C_nH_{2n} , are the most widely used linear hydrocarbon polymers. The versatility of these polymers arises from the fact that they are made from cheap petrochemical feed stocks through efficient catalytic polymerization process and ease of processing to various products. The range of their applications includes food packaging, textiles, lab equipment, and automotive components (Arutchelvi *et al.*, 2008).

In recent years, considerable attention has been focused on biodegradability of polymeric materials. Such materials need to be resistant to degradation both prior to and during use and should be capable of being degraded, if discarded after use, without causing any environmental problems (Upreti and Srivastava, 2003). Possible approach to reduce the 'vices of polymeric materials' is to identify potential microorganisms and develop protocol to effectively biodegrade the polymeric materials (Kawai, 1995).

Biodegradation is the result of the utilization of polymer as a carbon source by the microorganisms. This process is facilitated if the microorganism initially forms a biofilm over the polymer surface (Hadad *et al.*, 2005). Attempts to facilitate colonization of polyethylene by adding nonionic surfactants to the culture medium promoted the biodegradation of polyethylene (Albertsson *et al.* 1993; Ehara *et al.* 2000). Albertsson and Karlsson (1990) found that polyethylene subjected to 26 days of artificial UV irradiation before being buried in soil evolved less than 0.5% carbon (as CO_2) by weight after 10 years. Without prior irradiation, less than 0.2% carbon dioxide was produced. Earlier reports have shown that no signs of deterioration could be observed in polyethylene sheet incubated in moist soil for 12 years (Potts and Jelinek, 1978), and only partial degradation was observed in a polyethylene film buried in soil for 32 years (Otake *et al.*, 1995). Nevertheless, several studies have demonstrated partial

biodegradation of polyethylene after UV irradiation (Cornell *et al.*, 1984), thermal treatment (Huang *et al.*, 1990; Kwpp and Jewell, 1992) or oxidation with nitric acid (Mochizuki *et al.*, 1999). It is reported that there is a synergistic effect between photo-oxidation and biodegradation of polyethylene (Albertsson *et al.*, 1987). An increase in the biodegradation of polyethylene was observed with increase in the time of exposure to UV (Hadad *et al.*, 2005).

Biodegradation is aerobic in nature and can be carried out both by using mixed culture and pure cultures. The first report demonstrating bacterial degradation of the oxidized polyethylene in pure culture was described by Lee *et al.* (1991). The known lignin-degrading bacteria *Streptomyces viridosporus* T7A, *S. badius* 252, and *S. setonii* 75Vi2 and fungus *Phanerochaete chrysosporium* were used. They described the pure culture system for evaluating the biodegradability of degradable plastic films containing pro-oxidant and 6% starch. Biodegradability was evaluated by weight loss, tensile strength loss, changes in percent elongation, and changes in polyethylene molecular weight distribution.

Biodegradation of starch blended and modified PE with protein hydrolysate has also been studied (El-Shafei *et al.*, 1998). Studies carried out by Mezzanotte *et al.* (2004) were on three materials. The first one was a biodegradable polymer produced by Novamont (Italy), based on plastified starch complexed with a biodegradable synthetic polyester and commercially known as Mater-Bi NF01U. The second one was poly(ϵ -caprolactone) (PCL) produced by Dow (USA) and commercially designed as "Tone". Third material, microcrystalline cellulose is generally used as positive control in biodegradation tests. These three samples were tested using an inocula of activated sludges of three different types. According to their considerations they denoted three sludges as Sludge 1, Sludge 2 and Sludge 3. Sludge 1 and Sludge 2 were drawn from municipal wastewater treatment plants both of which received mixed sewage (domestic and industrial). Sludge 3 was obtained from an industrial membrane bioreactor treating waste water from a chemical-pharmaceutical site and thus had different biological and acclimation characteristics. Assessment of biodegradability was performed following the standard test method ISO 14851 which was based on the measurement of oxygen consumption caused by the respiration of the test material. This study confirmed that the origin of inoculum is an important source of

variability which can affect the evaluation of the degree of mineralization. The results indicated that variability was lower for cellulose than for other two materials.

Study carried out by Wang et al. (2005) was on a nanocomposites of polymer (PHBV) and clay (OMMT). Polymer/ OMMT nanocomposites have been attracting great interest because of their improved properties such as increased moduli and tensile properties. Biodegradation was carried out by them in the soil suspension. Soil samples were collected from the top soil of the farm field. After carrying out these experiments, significant changes in physical and chemical nature of the polymer PHBV were noticed. The results showed that the biodegradability of PHBV/ OMMT in soil suspension decreased with increasing amount of OMMT, which was in agreement with the results of the biodegradability for aliphatic polyester/ OMMT in activated soil

An experiment carried out by Pseja et al. (2006) deals with the blends composed of polyvinyl alcohol (PVA) and biopolymers. PVA does not belong to biologically inert plastics but its degradation rate is low. Degradation of PVA was studied in an aqueous anaerobic environment employing inoculation with digested activated sludge from municipal waste water treatment plant. The degree of degradation after modification with native or plasticized biopolymer such as starch increases in a strikingly manner at a starch level as low as 5 wt. %.

Kumar et al. (2006) performed experiments with commercial samples of isotactic polypropylene and heterophasic ethylene propylene copolymers. The compost was prepared from all the waste materials in suitable compositions, which include cow dung, saw dust, newspaper and computer paper, white bread, shredded leaves, food waste and urea with proper moisture content. There was a significant loss of weight, and fungal colonization was seen on the surface of samples. It was observed that photo-oxidative ageing directly enhanced the biodegradability of composites as the increase in fungal growth rate and decrease in weight during composting were found.

Du et al. (2006) studied the degradability of thermoplastic starch and thermoplastic dialdehyde starch under controlled composting conditions. Chemical modification of starch can have a major impact on the biodegradation rate and final biodegradation percentage. Mature compost was obtained from a composting plant in Beijing. TPS degraded faster than TPDAS under

controlled composting conditions. Degrading microorganisms for the starch tested were also isolated and screened from the compost.

Chiellini et al. (2003) carried out their work on undegraded and thermally fragmented low density polyethylene film samples containing totally degradable plastic additives pro-oxidants. Biodegradation tests were carried out in a cylindrical glass vessel containing a multilayer substrate in which defined amounts of forest sandy soil or mature compost was placed. Biodegradation extent of each test material was calculated as a percentage of overall theoretical CO₂ production on the basis of the determined carbon content of the samples. Results revealed that LDPE-TDPA formulations are effective in promoting the oxidation and subsequent biodegradation of polyethylene in soil environments.

The biodegradability of polyvinyl alcohol (PVA) was investigated by Solaro et al. (1998) under different conditions by respirometric determinations, iodometric analysis, and molecular weight evaluation. Microbial inocula derived from the sewage sludge of municipal and paper mill wastewater treatment plants were used. A rather active PVA-degrading bacterial mixed culture was obtained from the paper mill sewage sludge. Significant biodegradation levels within quite short incubation times were obtained in liquid cultures in the presence of acclimated microbial populations. The influence of some polymer properties such as molecular weight and degree of hydrolysis on the biodegradation rate and extent was investigated in the presence of either the acclimated mixed bacterial culture or its sterile filtrate. The molecular weight appeared to be not a limiting factor of microbial attack. Comparison of the degradation process in the presence of either bacterial cells or their culture filtrate highlighted the ability of some microbial strains to utilize polymer chains having 5–10 kD molecular weight.

Sasek et al. (2006) conducted experiments on copolymers and aromatic and aliphatic copolyesters. Composting was run under controlled conditions in a thermal insulated composting chamber using a standard mixture of raw material used for cultivation of white mushroom obtained from a local mushroom compost-producing company. Specimens of polymeric foils in small stainless steel containers were buried in the compost pile for different time periods. After

the completion of the experiments changes were detected in copolyester filaments through SEM which showed positive results because polymer backbone was cleaved.

Kleeberg et al. (1998) studied the biodegradation of copolyesters made of 1,4-butanediol, terephthalic acid, and adipic acid. They also studied it in mixed culture conditions aerobically by the use of compost made from green waste. Studies showed a significant change in the properties denoting the degradation of polyester films.

Tadros et al. (1999) carried out their studies on thermoplastic as well as on thermosetting copolyesters and studied their degradation behaviour by preparing a mixed cultures of spores and bacteria prepared from separate cultures.

Rudeekit et al. (2003) compared degradation of biodegradable plastics by aerobic microorganisms by employing various standard methods. Testing soil was used to perform the biodegradation of various plastics obtained from composting of organic agricultural waste. Plastic samples used were filter paper as positive standard, LDPE as negative standard, LDPE/starch blends and starch foam. This work was conducted to compare the biodegradation of biodegradable plastics. The results show that the biodegradation of cellulose as positive control was 4.06%. The LDPE/starch blends were degraded 3 and 6 times of filter paper respectively. Whereas, the biodegradation of filter paper was 11.78%. These data show that polymers degraded significantly using mixed culture and shows positive results.

Yang et al. (2004) tested biodegradation of plastics in compost with animal fodder. Polypropylene (PP) was chosen as non-degradable plastic. Poly(L-lactic acid) (PLLA) and poly(butylene succinate) (PBS) were chosen as slowly degrading plastics while polycaprolactone (PCL) and poly(butylenes succinate-co-adipate) (PBSA) were chosen as easily degradable plastics. The composition of fat, fibre and protein in animal fodder was same as that of food garbage. This experiment was performed taking several shapes of polymers and evaluating the effect of biodegradability on different shapes of polymers.

Jakubowicz (2002) tested the polyethylene films containing a pro-oxidant Mn-stearate, and were thermally oxidized before undergoing the real biodegradation process in mixed cultures or under

composting conditions. The thermally oxidized materials were called as pre-aged materials. Precise amount of the test materials was mixed with microbial activated soil, composed of 90% plant substrate and 10% mature compost. Mature compost consisted of a large number of different microorganisms that normally occur in a compost and which are able to degrade different types of biodegradable compounds. The investigation showed that degree of bioassimilation was increasing continuously.

Four commercialized biopolymers were used by Rosa et al. (2002) for degradation tests in a model waste landfill reactors. Plastic materials used were: PHBV, PCL, SPVA and CA plastic. Mixed culture used by them was synthesized waste which contained equivalent weights of yard waste, kitchen garbage, paper waste, dry dog-food, dewatered sludge and soil. Plastic film was placed in the middle of this heap. This experiment was performed both aerobically and anaerobically. The results indicated the existence of the great variations in the degradability of BPs in aerobic and anaerobic environment of landfills.

Roy et al. (2008) studied the degradation of abiotically aged LDPE films containing a pro-oxidant by bacterial consortium. The films were initially subjected to an abiotic treatment comprising UV-irradiation, and subsequently inoculated with bacterial strains. The spectroscopic investigation revealed that the strains preferentially consumed the oxygenated products leading to decrease in the carbonyl index.

Nanda et al. (2009) conducted their experiments on untreated (PP-UT) and thermally pretreated (at 80 °C for 10 days) polypropylene (PP-TT) films of 0.05 mm thickness were subjected to *in vitro* biodegradation in minimal medium with mixed soil culture for 12 months. The results indicated that the ester carbonyl index in PP-TT increased up to 9 months and later decreased indicating abiotic followed by biotic process. No such changes were observed with PP-UT. Methyl group index decreased in both the cases indicating oxidation at the primary carbon. These results showed significant degradation of polypropylene films in mixed culture environments.

Reddy et al. (2009) studied that montmorillonite clay has been reported to promote the growth of microbes on polyethylene by keeping the pH of the environment at levels conducive to growth.

In an attempt to improve the overall oxo-biodegradation of polyethylene, montmorillonite nanoclay was used in the study along with a pro-oxidant. Film samples of oxo-biodegradable polyethylene (OPE) and oxo-biodegradable polyethylene nanocomposite (OPENac) were subjected to abiotic oxidation followed by microbial degradation using microorganism *Pseudomonas aeruginosa*. FTIR results show that the abiotic oxidation of polyethylene was influenced significantly by the pro-oxidant but not by nanoclay. It indicates that nanoclay, by providing a favourable environment, helps in the growth of the microorganism and its utilisation of the polymer surface and the bulk of the polymer volume.

Singh et al. (2010) carried out their experiments on the blends of polyethylene samples with polylactide (PLLA). Melt blending of linear low density polyethylene (LLDPE) and polylactide (PLLA) was performed in an extrusion mixer with post extrusion blown film attachment with and without compatibilizer-grafted low density polyethylene maleic anhydride. The blend compositions were optimized for tensile properties as per ASTM D 882-91. Based on this, LLDPE 80 (80 wt% LLDPE & 20 wt% PLLA) and M-g-L 80/4 (80 wt% LLDPE, 20 wt% PLLA and 4 parts compatibilizer per hundred parts of resin) were found to be an optimum composition. FTIR reveals that the presence of compatibilizer shifts carbonyl peak hence some increase in interaction between LLDPE and PLLA.

Based on the literature one could conclude that pretreated polymers degrade more easily than the untreated polymers and degradation leads to decrease in molecular weight, tensile strength, viscosity and formation of new functional groups such as carbonyl, hydroxyl, etc.

This course of work focuses on the degradation studies of linear low density polyethylene and its blends by using compost as the source of mixed culture. Compost consists of several microorganisms which consume the polymer after composting as their sole carbon source. Chapters to follow reveals the materials used for analysis, methods adopted for the degradation and the analytical procedures applied for confirming the degradation of samples.

Chapter 3

MATERIALS & METHODS

3.1 Materials

3.1.1 Plastic films

In the present investigation, pure linear low density polyethylene (LLDPE 100), LLDPE 80 (80 wt % LLDPE & 20 wt % poly(l-lactic acid) (PLLA), LLDPE 80/4 (80 wt % LLDPE, 20 wt % PLLA and 4 parts compatibilizer (grafted low density polyethylene maleic anhydride) per hundred parts of resin) films of size 80×25 mm with thickness 0.125 mm were made by melt blending of LLDPE and PLLA in an extrusion mixer with post extrusion blown film attachment with and without a compatibilizer which were reported of our earlier work (Singh *et al.*, 2010). The market available biodegradable polymer films of size 80×25 mm with thickness 0.11 mm were kindly provided by M/s Balson Industries, Pune, Maharashtra, India (www.balsonindustries.com).

3.1.2. Compost

The mature compost (municipal solid waste) was obtained from a compost plant, New Delhi Municipal Council, Okhla, New Delhi, India. The compost inoculum which came from the organic fraction of municipal solid waste was crushed into fine powder and sieved on a screen of < 10 mm. The compost inoculum was made free from larger inert materials (glass, stones, metals, etc.) as much as possible. These items were removed manually as much as possible to produce a homogenous compost inoculum. The compost had the following basic properties: total solids (TS) 81%; volatile solids at 550⁰C (VS)18%; pH 7.2; C/N ratio 15.3. This was used for the composting of the samples.

3.2 Methodology

3.2.1 Pretreatment of polymers

The polymer films were cut into small pieces (6 cm × 6 cm) and were weighed, disinfected in 70% ethanol for 30 minutes and air-dried for 15 minutes in laminar air flow chamber. Ethanol was used to remove any organic matter adhering to the surface. Then the films in duplicates were buried in trays, each having 600 g of compost.

3.2.2. ASTM D5338 (2003) standard for aerobic treatment using municipal solid waste compost

The plastic films, market available biodegradable polymer, LLDPE 100 & its blends (LLDPE 80, LLDPE 80/4) were treated under controlled composting conditions according to Modified ASTM standard D5338-98. Four composting vessels (one blank, one positive, one negative and one test sample) of 3 L capacity were used for the study. Each composting vessels contained 600g of compost, three samples of 2 g each and 1 L of distilled water. For CO₂ trapping, three 5000-mL bottles fitted with gas sparging and containing Ba(OH)₂ solution were used. The composting vessels were incubated for a period of 45 days. Initially, the incubation temperature was maintained at 35⁰C (± 2⁰C) for a period of one day to stimulate a mesophilic start-up phase. Subsequently, the temperature was raised to 58⁰C (± 2⁰C) and maintained for a period of four days. After this sanitizing period, the temperature was reduced to 50⁰C (± 2⁰C) for optimum composting conditions and maintained until day 28. Temperature was then reduced to 35⁰C (± 2⁰C) for the remainder of the test period to simulate a mesophilic curing phase. The incubation time of 45 days may be extended until no significant CO₂ production in excess of the inoculum is recorded for a period of one week.

3.2.3. Controlled Composting (Modified ASTM 5338(2003))

The compost inoculum was crushed well-aerated and sieved on a screen of < 10 mm. The compost inoculum was free from larger inert materials (glass, stones, metals, etc.) as possible. The plastic films, market available biodegradable polymer, LLDPE 100 & its blends (LLDPE 80, LLDPE 80/4) were embedded in the compost and incubated in incubator Model NSW-152 of Narang Scientific Works Pvt. Ltd., India for a period of 45 days, initially kept at 37⁰C for a period of one day to stimulate a mesophilic start-up phase. Subsequently, the temperature was raised to 50⁰C for a period of four days for optimum composting conditions. Then the temperature was reduced to 37⁰C for the remainder of the test period to stimulate a mesophilic start up phase. Moisture conditions and aerobic conditions were maintained manually as much as possible for controlled composting.

3.3 Analytical/ Testing procedures

3.3.1 Determination of dry weight of residual polymer

A simple and quick way to measure the biodegradation of polymers is by determining the weight loss. Microorganisms that grow within the polymer lead to an increase in weight due to accumulation, whereas a loss of polymer integrity leads to weight loss. Multiple samples were weighed with an accurate four-digit balance and average values were reported.

To facilitate accurate measurement of the weight of the residual polyethylene, the bacterial biofilm was washed off the polymer surface with a 2% (v/v) aqueous sodium dodecyl sulphate solution for 4 h and then with distilled water. The washed polymer film was placed on a filter paper and dried overnight at 60⁰C before weighing. The initial weights of the pre-incubated polyethylene samples were also measured following the same procedure as mentioned above.

3.3.2. Fourier transform infrared (FTIR) and attenuated total reflectance (ATR) spectroscopy

In infrared spectroscopy, IR radiation is passed through a sample. Some of the infrared radiation is absorbed by the sample and some of it is passed through (transmitted). The resulting spectrum represents the molecular absorption and transmission, creating a molecular fingerprint of the sample. Like a fingerprint no two unique molecular structures produce the same infrared spectrum. Infrared spectroscopy has been a workhorse technique for materials analysis in the laboratory for over several years. An infrared spectrum represents a fingerprint of a sample with absorption peaks which correspond to the frequencies of vibrations between the bonds of the atoms making up the material. Because each different material is a unique combination of atoms, no two compounds produce the exact same infrared spectrum. Therefore, infrared spectroscopy can result in a positive identification (qualitative analysis) of different kinds of material. In addition, the size of the peaks in the spectrum is a direct indication of the amount of material present. With modern software algorithms, infrared is an excellent tool for quantitative analysis. . So degradation products, chemical moieties incorporated into the polymer molecules such as branches, co-monomers, unsaturation and presence of additives such as antioxidants can be determined by this technique. Fourier transform-attenuated total reflectance (FT-ATR) infrared spectroscopic studies were carried out on film samples using a Thermo Scientific FT-IR spectrophotometer (Model Nicolet iS10) in the horizontal ATR mode, using a zinc-selenide crystal. A total of 32 scans were taken with a resolution of 4 cm^{-1} . It was used to detect the degradation on the basis of changes in the functional groups. A spectrum was taken at 400 to 4000 cm^{-1} wave numbers for each sample.

3.3.3 Estimation of microbial biomass colonizing the polymers

As the microbial cells were strongly attached to the polymer surfaces, it was impossible to estimate the population density by standard techniques, such as direct cell counting or plating. Therefore, the population density of the biofilm on the polyethylene surface was estimated by determining the concentration of extractable protein. Colonized polymer samples taken from the compost were washed briefly with water and then boiled for 30 min in 5 ml of 0.5 N NaOH. The suspension was centrifuged at 10,000 rpm, 4°C for 15 min, and the supernatant was kept aside

and the pellet was subjected to the same procedure once again. The two supernatants were combined and the protein concentration was determined according to Folin-Lowry method as described by Lowry et al. (1951) using bovine serum albumin (BSA) as a standard.

Chapter 4

RESULTS AND DISCUSSION

This chapter deals with the results obtained after composting of polyethylene samples and its blends. The results of weight loss, FTIR analysis and protein estimation have been given and discussed for the significant changes.

4.1 Percentage Weight Loss

Changes due to bacterial degradation were assessed qualitatively by measuring weight loss of polymer. The weight loss of polymer after incubation may be purely because of microbial activity.

Our standard biodegradation assay for LLDPE and its blends lasts for 45 days. During this period, the microbes utilized the carbonyl residues and reduce their concentration. After the incubation period, the polyethylene samples were washed, dried and weighed.

A maximum weight loss of approximately 18% was observed with market available biodegradable polymer under controlled composting conditions within 45days. Weight loss of 5.5% with LLDPE 80/4, 5.3% with LLDPE 80/20 and 0.83% with LLDPE under compost was observed. Karlsson and Albertsson (1998) have also reported that the total weight loss during degradation was 16 % and in addition to H₂O and CO₂, shorter hydrocarbons, alcohols, organic acids, ketones, aldehydes, etc. are also formed.

Table 4.1. Percentage weight loss of plastic films under compost

Sample	Weight of polymers before composting (g)	weight of polymers after composting (g)	Weight loss (%)
LLDPE 100	0.1438	0.1426	0.83
LLDPE 80/20	0.2017	0.1910	5.30
LLDPE 80/4	0.1892	0.1788	5.49
Biodegradable polymer	0.0518	0.0426	17.76

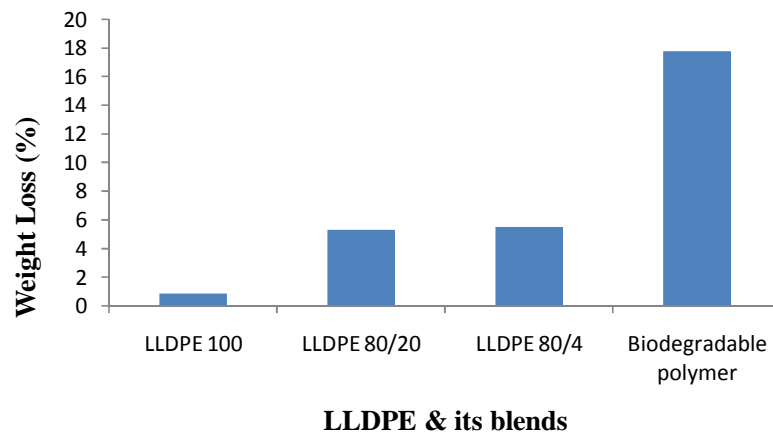


Fig 4.1. Percentage weight loss after composting

4.2 Protein estimation

Biofilm formation on polymer surfaces was monitored by quantifying the total proteins extracted from the biofilm. The readings were taken after the interval of 15, 30 and 45 days at 660 nm. The OD was compared with the OD of the known sample i.e. bovine serum albumin (BSA) was taken as standard in this case.

Table 4.2. Estimation of protein concentration

Incubation time (days)	Protein concentration ($\mu\text{g/ml}$)			
	LLDPE films	LLDPE 80/20 films	LLDPE 80/4 films	Biodegradable Polymer
0	0.02	0.04	0.045	0.03
15	3.2	5.7	5.9	8.2
30	1.8	2.6	2.3	5.6
45	0.7	0.5	0.6	1.0

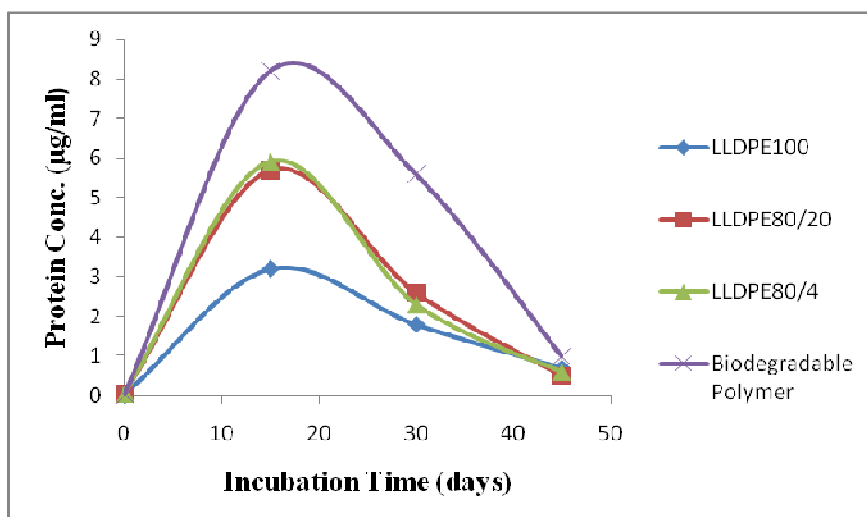


Fig 4.2. Comparison of protein conc. in LLDPE and its blends

Fig. 4.2. shows a biphasic pattern of biofilm formation on the polymer surfaces. The first phase was characterized by a steep increase in protein content during the first 13-17 days of incubation, reflecting an increase in the biofilm biomass. This phase was followed by a second period in which the protein content came to a low level and after some time their concentration remained constant. Fig. 4.2. also represents the comparison of the concentration of protein extracted from LLDPE and its various blends taken in the form of films.

4.3 Fourier transform infra-red (FTIR) spectroscopy

Fourier transform infrared spectroscopy (FTIR) analysis is a useful tool to determine the formation of new or disappearance of functional groups. So degradation products, chemical moieties incorporated into the polymer molecules such as branches, co-monomers, unsaturation and presence of additives such as antioxidants can be determined by this technique.

FTIR spectroscopy was performed to check the biodegradation of polymer films by the action of microorganisms present in municipal solid waste compost. FTIR analysis of pure polyethylene films and that of its blends before and after composting were compared and the results are evaluated by the formation of new peaks or their disappearance in the studied range. The graph is plotted between the % transmittance on Y- axis and wavelength in cm^{-1} on X-axis. Peaks present at $2865\text{-}2845\text{ cm}^{-1}$ are due to methylene C-H symmetric stretch. FTIR analysis of polymer films showed decrease in peak from wavelength 2926.42 cm^{-1} to 2924.43 cm^{-1} (as shown in fig. 4.3-4.4). The decrease indicated the cleavage of C-H bonds. Peaks appearing in the range of $1485\text{-}1445\text{ cm}^{-1}$ are due to methylene C-H bend. After analysis it was found out that peaks are also emerging at the wavelength of 1134 cm^{-1} as well as at 1050 cm^{-1} and were found out to be due to tertiary alcohol C-O and primary alcohol C-O stretch respectively. The appearance of some new peaks at $1400\text{-}1600$ indicated the formation of new intermediate functional groups

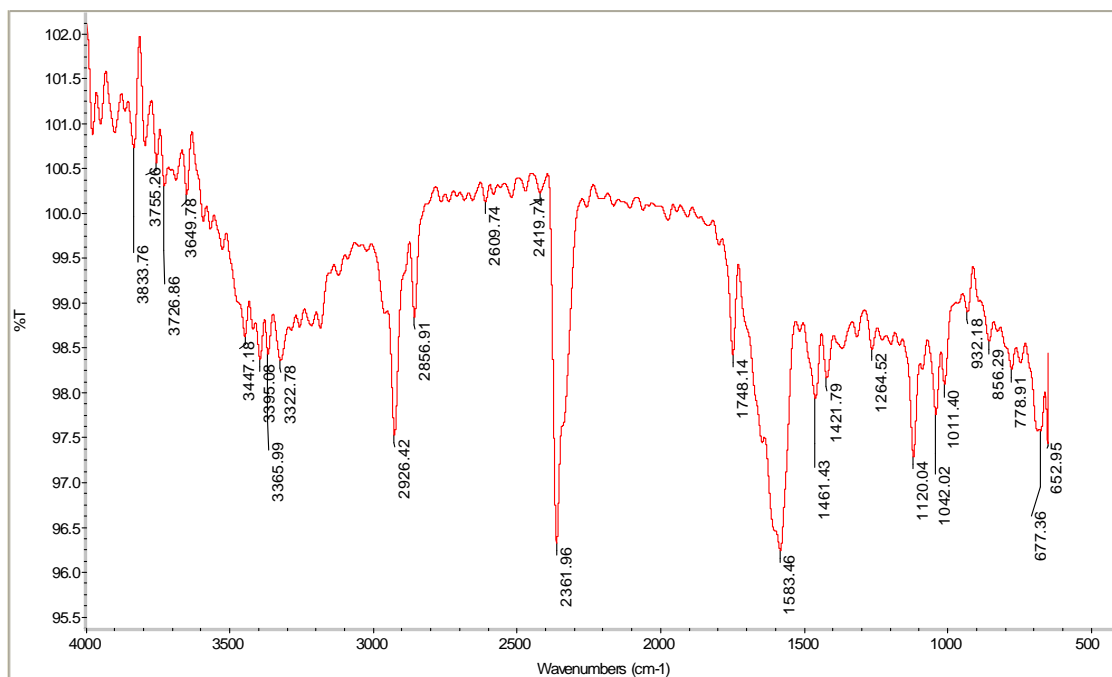


Fig. 4.3 FTIR spectra of LLDPE before composting

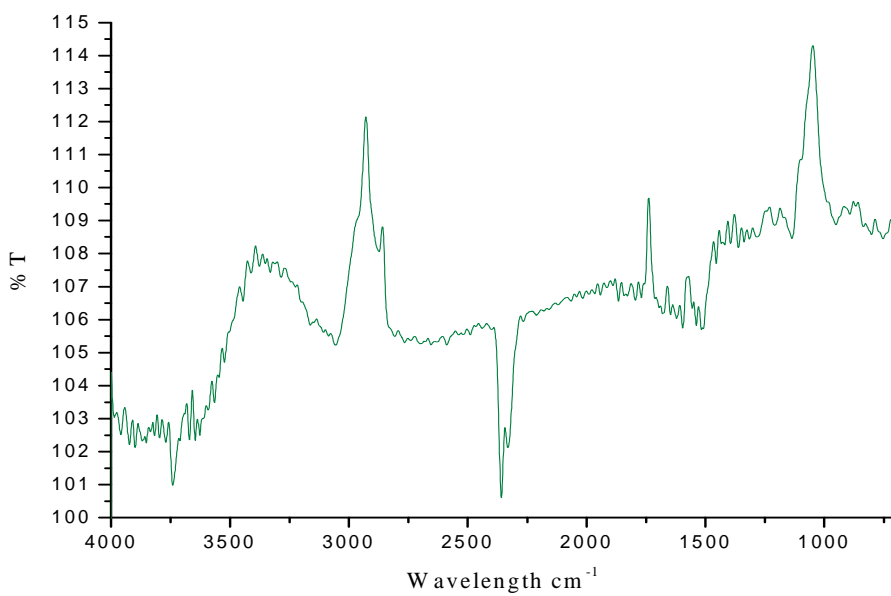


Fig 4.4 FTIR spectra of LLDPE after composting

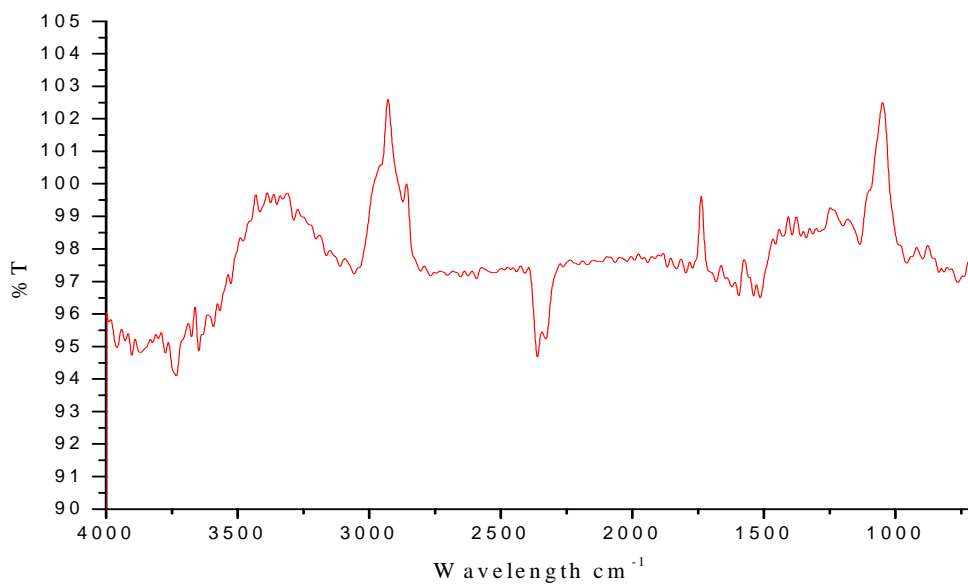


Fig 4.5 FTIR spectra of LLDPE 80/20 before composting

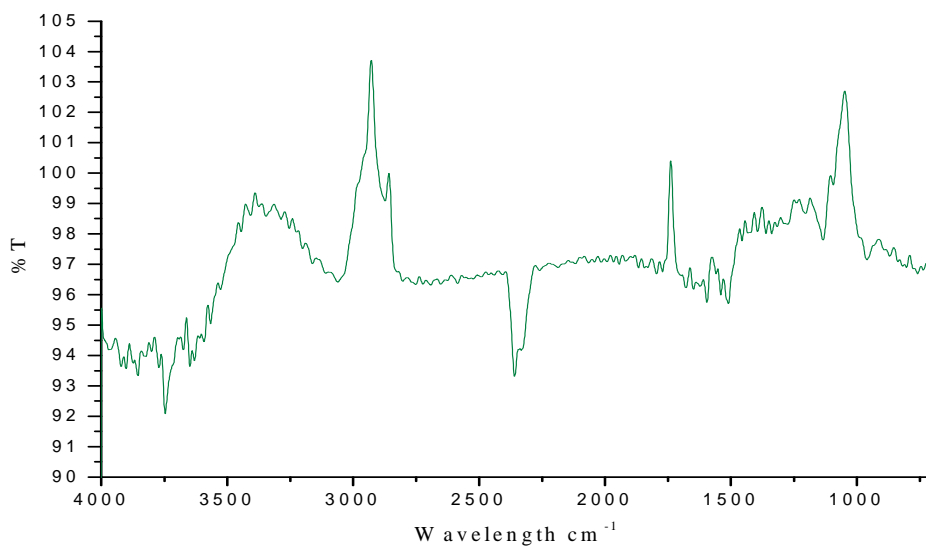


Fig 4.6 FTIR spectra of LLDPE 80/20 after composting

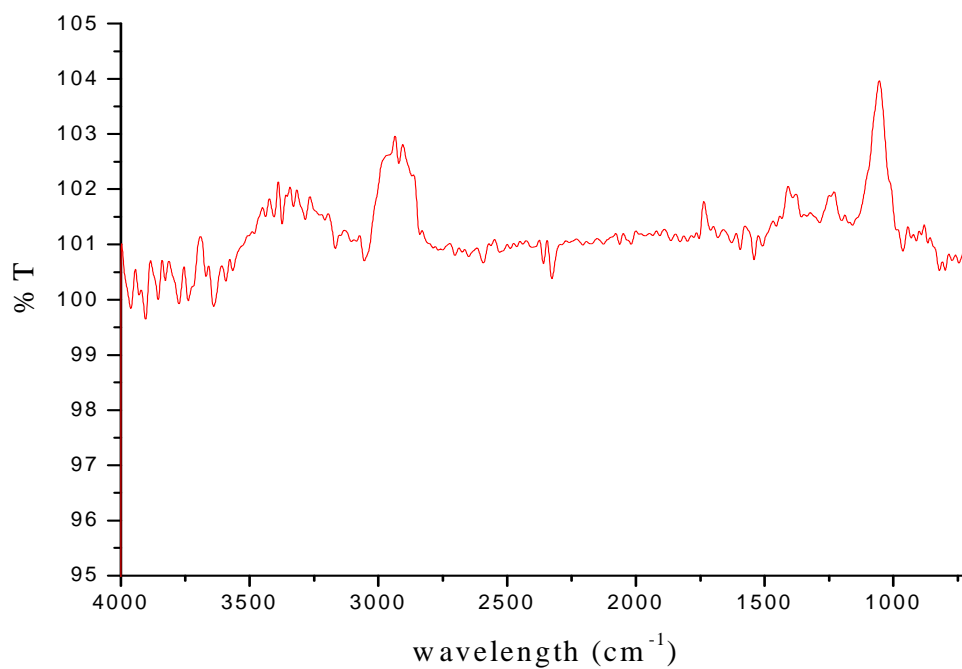


Fig 4.7 FTIR spectra of LLDPE 80/4 before composting

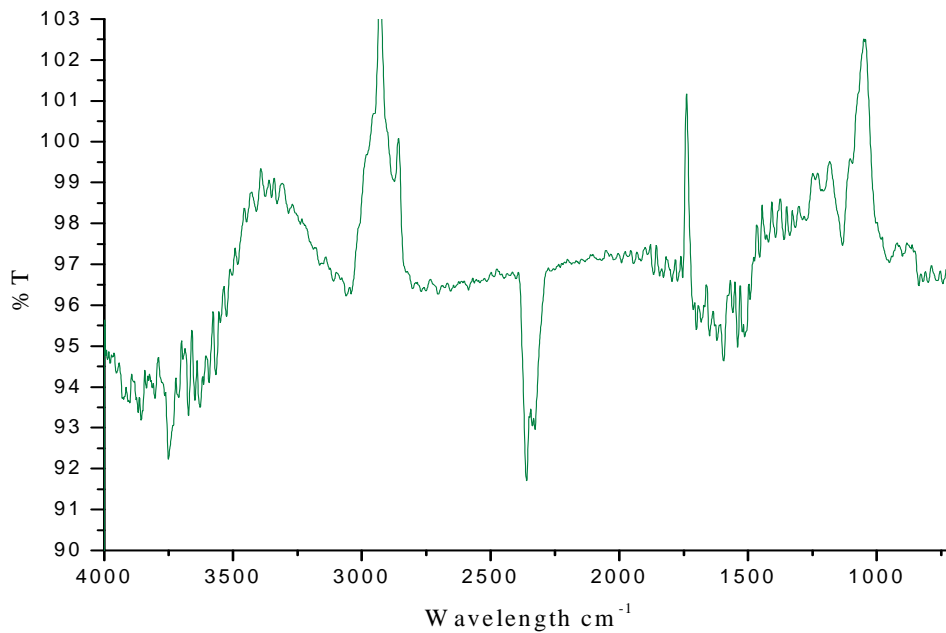


Fig 4.8 FTIR spectra of LLDPE 80/4 after composting

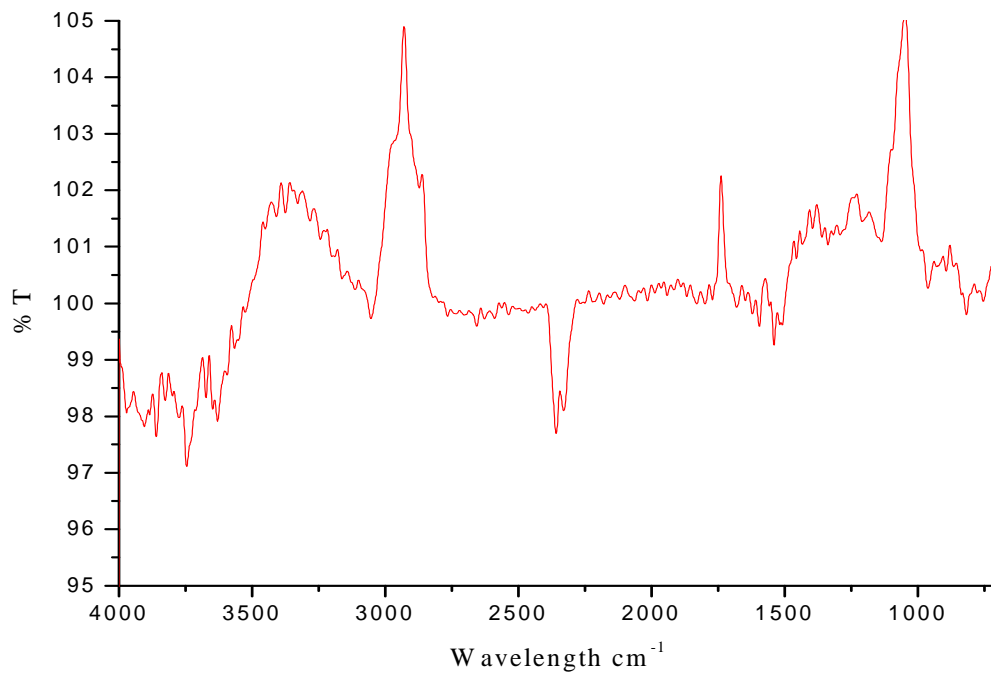


Fig 4.9 FTIR analysis of biodegradable polymer before composting

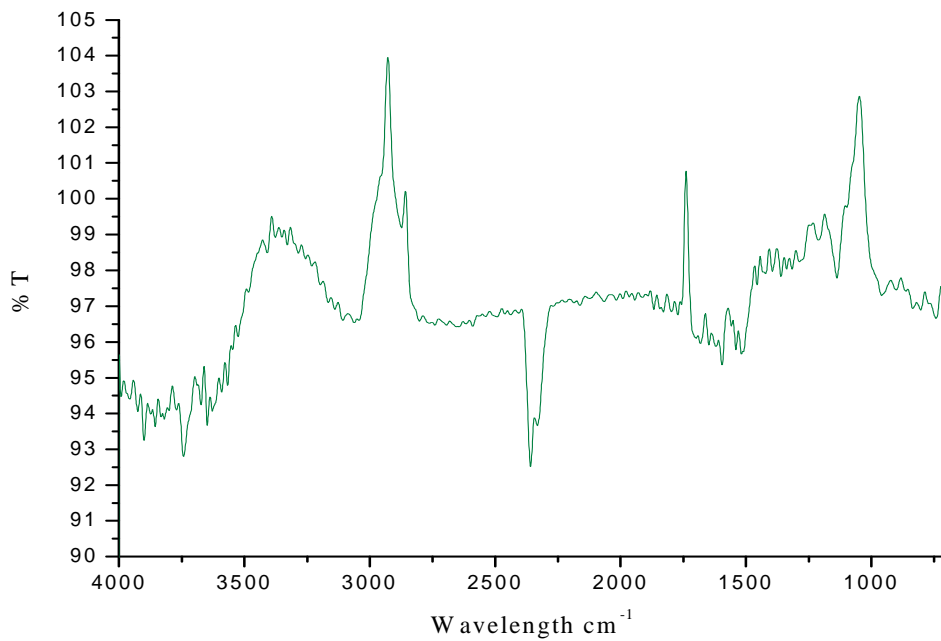


Fig 4.10 FTIR analysis of biodegradable polymer after composting

Composting of LLDPE 80/20, LLDPE 80/4 showed a marked reduction in the amount of carbonyl residues. These results confirmed the degradation of polymer films by composting to much extent because as the polymer is degraded then this degradation results in the disintegration of few bonds between various atoms thus resulting in the formation of simpler molecules such as monomers oligomers and dimers etc. as well as formation of some new bonds between various atoms. As the bonds are lost or disappeared, the functional group based on that bond is now no longer present in that compound. This disappearance of functional groups is represented by the spectra and thus in this way the analysis is performed

Chapter 5

CONCLUSIONS AND FUTURE PROSPECTS

5.1 Conclusions

Polyethylene is widely used as a packaging material. Traditionally, the polyethylene was non-biodegradable.

Biodegradation of LLDPE and its blends in municipal solid waste compost was very fast. The film was assimilated by the microorganisms upto some extent over the period of 45 days. The obtained results indicate that LLDPE and its blends were very sensitive to enzymatic attack of microorganisms in living environment.

Various testing methods were applied to the films under compost and each method revealed positive results for biodegradation.

Weight loss of the polymer films was obtained as high as 6% approximately showing a significant decrease in the weight of polymer and thus significant biodegradation of the polymer films.

FTIR spectra also confirms the biodegradation of polymer as some chemical changes are seen by polymers when results of before and after composting were compared.

This study demonstrates that polymers, considered to be inert, can be biodegraded if the right conditions for their biodegradation is used. Controlled composting conditions were effective for enhancing the capabilities of a microbes capable of utilizing LLDPE and its blends as the sole carbon and energy sources.

5.2 Future prospects

- ✓ Composting according to ASTM D5338 needs more detailed study to know the fate of these organic polymers in the environment and the time required for their total mineralization to CO₂ have yet to be fully understood.
- ✓ Composting under controlled conditions gave appreciably very good results in a very short duration ie. 28 days. May be if the time interval for composting conditions is increased it could produce better results.
- ✓ Modification of the type of polymer used for degradation by composting can result in the alleviation of pollution problems caused by various polymers other than LLDPE to the environment.
- ✓ Modification of blends of polymers and thus comparative study resulting in the type of blend which makes the polymer more biodegradable
- ✓ Source of mixed cultures can be varied and comparative study revealing the type in which maximum biodegradation occurs can be carried out

References

- Alauddin M, Choudkury I A, Baradie M A, Hashmi M S J, Plastics and their machining: a review, *Materials Processing Technology*, 54(1999): 40–46.
- Albertsson A C and Karlsson S, The influence of biotic and abiotic environments on the degradation of polyethylene, *Progress in Polymer science*, 15(1990): 177-192.
- Albertsson A C, Erlandsson B, Hakkarainen K, Karlsson S., Molecular weight changes and polymeric matrix changes correlated with the formation of degradation products in biodegraded polyethylene., *Journal of Environmental Polymer Degradation*, 6(1998): 187-195.
- Albertsson A C, Sares C, Karlsson S, Increased biodegradation of LDPE with nonionic surfactants, *Acta. Polym.*, 44(1993): 243-246.
- Albertsson A.C., Andersson S.O. and Karlsson S., The mechanism of biodegradation of polyethylene, *Polymer Degradation and Stability*, 18(1987): 73-87.
- Allen A B, Hilliard N P, and Howard G T, Purification and characterization of a soluble polyurethane degrading enzyme from *Comamonas acidovorans*, *Int. Biodeterioration & Biodegradation*, 43(1999): 37–41.
- Ammas W., Ammas A., Tighe B., A Review of Biodegradable Polymers: Uses, Current Developments in the Synthesis and Characterization of Biodegradable Polyesters, Blends of Biodegradable Polymers and Recent Advances in Biodegradation Studies., *Polymer International* 47(1998): 89-144.
- Anonymous, Ecological assessment of ECM plastics, Microtech Research Inc., Ohio, Report by Chem Risk- A service of Mc Laren Hart Inc. Ohio, (1999): 14.
- Arutchelvi J., Sudhakar M., Arkatkar A., Doble M., Bhaduri S., and Uppara P.V., Biodegradation of polyethylene and polypropylene, *Indian Journal of Biotechnology*, 7(2008): 9-22.
- Bastioli C., Handbook of biodegradable polymers, Rapra Technology Limited, United Kingdom, 2005.

Chiellini E, Corti A & Swift G, Biodegradation of thermally- oxidized, fragmented low density polyethylene, *Polym Degrad Stab*, 81(2003): 341-351.

Cornell J H, Kaplan A M, Rogers M R, Biodegradation of photooxidized polyalkylenes, *J. Appl. Polym. Sci*, 29 (1984): 2581-2597.

Du Y.L., Cao Y., Lu F., Li F., CaoY., Wang X.L., Wang Y.Z., Biodegradation behaviors of thermoplastic starch (TPS) and thermoplastic dialdehyde starch under controlled composting conditions, *Polymer Testing* 27(2006): 924-930.

Ehara K, Lioyshi Y, Tsutsumi Y, Nishida T, Polyethylene degradation by manganese peroxidase in the absence of hydrogen peroxide, *J. Wood Sci.*, 46(2000): 180-183.

El-Shafei H.A., El-Nasser N.H.A., Kansoh A.L. and Ali A.M., Biodegradation of disposable polyethylene by fungi and *Streptomyces* species, *Polymer Degradation and Stability*, 62(1998): 361-365.

Hadad D., Geresh S. and Sivan A., Biodegradation of polyethylene by the thermophilic bacterium *Brevibacillus borstelensis*, *Journal of Applied Microbiology*, 98(2005): 1093-1100.

Huang J, Shetty A S, Wang M, Biodegradable plastics: A review. *Adv. Polym. Technol.*, 10 (1990): 23-30.

Jakubowicz I., Evaluation of Degradability of Biodegradable Polyethylene, *Science Direct: Polymer Degradation and stability* 80(2002): 39-43.

Jayasekara R., Harding I., Bowater I. and Lornergan G., Biodegradability of selected range of polymers and polymer blends and standard methods for assessment of biodegradation, *Journal of Polymers and the Environment*, 13(2005): 231-251.

Kawai F., Bacterial degradation of glycol ethers, *Applied Microbiology and Biotechnology*, 44(1995): 532-538.

Kleeberg I., Hetz C., Kroppenstedt R.M., Deckwer W.D., Biodegradation of Aliphatic and Aromatic copolyesters by *Thermonospora Fusca* and other thermophilic compost isolates, Appl. Environ. Microbiol. 64(1998): 1731-5.

Krzan A., Hemjinda S., Miertus S., Corti A. and Chiellini E., Standardization and certification in the area of environmentally degradable plastics, Polymer Degradation and Stability, 91(2006): 2819-2833.

Kumar A.P., Pandey J.K., Kumar B., Singh R.P., Photo-/Bio-degradability of agrowaste and ethylene- propylene copolymer composites under abiotic and biotic environments, J. polymer environ 14(2006): 203-212.

Kwpp L R and Jewell W J, Biodegradability of modified plastic films in controlled biological environments, Environ. Technol., 26(1992): 193-198.

Kyrikou I. and Briassoulis D., Biodegradation of agricultural plastic films: A critical review, Journal of Polymers and the Environment, 15(2007): 125-150.

Lee B., Pometto III A.L., Fratzke A. and Bailey T.B., Biodegradation of degradable plastic polyethylene by *Phanerochaete* and *Streptomyces* species, Applied and Environmental Microbiology, 57(3)(1991): 678-685.

Lowry O.H., Rosebrough N.J., Farr A.L. and Randall R.J., Protein measurement with the folin phenol reagent, The Journal of Biological Chemistry, 193(1951): 265-275.

Massardier-Nageotte V, Pestre C, Cruard-Pradet T, Bayard R, Aerobic and anaerobic biodegradability of polymer films and physico-chemical characterization, Polymer Degradation and Stability, 91(2006): 620-627.

Mezzanotte V., Bertani R., Innocenti F.D., Tosin M., Influence of inocula on the results of biodegradation tests, Science Direct: Polymer Degradation and Stability 87(2004): 51-56.

Mochizuki M, Hayashi T, Nakayama K, Masuda T, Studies on biodegradable poly (hexano-6-lactone) fibers, Part 2: Environmental degradation (Technical Report), Pure Appl. Chem., 71 (1999): 2177-2188.

Nanda S., Sahu S.S., and Abraham J., Studies on the biodegradation of natural and synthetic polyethylene by *Pseudomonas*, Journal of Applied Sciences & Environmental Management, 2010; 14(2): 57-60.

Otake Y, Kobayashi T, Ashabe H, Murakami N, Ono K, Biodegradation of low-density polyethylene, polystyrene, polyvinylchloride and urea-formaldehyde resin buried under soil for over 32 years, J. Appl. Polym. Sci., 56(1995): 1789-1796.

Potts J E, Jelinek H H G, Aspect of Degradation and Stabilization of Polymers. Elsevier, New York, (1978): 617-658.

Pseja J., Charavatova H., Hruzik P., Hrcirik J., Kupec J., Anaerobic biodegradation of blends based on polyvinyl alcohol, J polymer environ 14(2006): 185-190.

Reddy N., Nama D., Yiqi Y., Polylactic acid/ Polypropylene Polyblend fibers for better resistance to degradation, Polymer degradation and stability, 93(2008): 233-241.

Rosa D.S., Filho R.P., Chui Q.S.H., Calil M.R., Guedes C.G.F, The Biodegradation of poly- β -(hydroxybutyrate), poly- β -(hydroxybutyrate-co- β -valerate) and poly(ϵ -caprolactone) in compost derived from municipal solid waste, European Polymer Journal 39(2002): 233-237.

Roy P.K., Titus S., Surekha P., Tulsi E., Deshmukh C., Rajagopal C., Degradation of abiotically aged LDPE films containing pro-oxidant by bacterial consortium, Science Direct: Polymer Degradation and Stability 57(2008): 1-6.

Rudeekit, Yosita., Leejakpai, Thanawadee, Euaphantasate, Nukul., Kongsuwan, Kongkiat, Comparative degradation of biodegradable plastics by aerobic microorganisms using ASTM D 5338-98(03) and ASTM 5988-03 as standard methods, 2003

Sasek V., Vitasek J., Chromcova D., Prokopova I., Brozek J., Nahlik J., Biodegradation of Synthetic Polymers by Composting and Fungal Treatment, Folia Microbiol., 51(2006): 425-430.

Scott G., 'Green' polymers, Polymer Degradation and Stability, 68(1999): 1-7.

Shah A.A., Hasan F., Hameed A. and Ahmed S., Biological degradation of plastics: A comprehensive review, *Biotechnology advances*, 26(2008): 246-265.

Singh G, Bhunia H, Rajor A, Jana R N, Choudhary V., Mechanical properties and morphology of polylactide, linear low-density polyethylene and their blends, *Journal of Applied Polymer Science*, 2010.

Solaro R., Corti A., Chilleni E., A new respirometric test simulating soil burial conditions for the evaluation of polymer biodegradation, *J Environ Polym Degrad*, 6(1998): 203-8.

Sudhakar M., Doble M., Murthy P.S., Venkatesan R., Marine microbe- mediated biodegradation of low- and high- density polyethylenes, *International Biodeterioration & Biodegradation*, 61(2007): 203-213.

Tadros R. M., Nouredni H., Timm D. C., Biodegradation of Thermoplastic and thermosetting Polyesters from Z-Protected Glutamic Acid, *Chemical and Biomolecular Engineering Research and Publications* (1999), University of Nebraska Lincoln

Tokiwa Y., Calabia B.P., Ugwu C.U. and Aiba S., Review: Biodegradability of plastics, *International Journal of Molecular Sciences*, 10(2009): 3722-3742.

Upreti M.C. and Srivastava R.B., A potential *Aspergillus* species for biodegradation of polymeric material, *Current Science*, 84(11)(2003): 1399-1402.

Wang S., Song C., Chen G., Guo T., Liu J., Zang B., Takeuchi S., Characteristics and biodegradation properties of poly(3-hydroxybutyrate-co-3-hydroxyvalerate)/organophilic montmorillonite (PHBV/OMMT) nanocomposites, *Science Direct: Polymer Degradation And Stability*, 87(2005): 69-76.

Yang H.S., Yoon J.S., Kim M.N, Dependence of biodegradability of plastic in compost on the shape of specimens, *polymer degradation and stability*, 87(2004): 131-135.

Zheng Y., Yanfu E.K., Bassi A.S., A Review of Plastic Waste Biodegradation, *Critical reviews in biotechnology*, 25(2005): 243-250.

Publications

1. Bansal M, Jain K, **Sharma A**, Bajpai P K and Bhunia H. “Current trends in microbial degradation studies of polymers” 14th Punjab Science Congress, SLIET, Longowal Feb 7-9, 2011: 100.
2. Bansal M, Jain K, **Sharma A**, Bajpai P K and Bhunia H. “Microbial degradation studies of Polymer” Proc. Advances in Chemical Engineering 2”, Macmillan Publishers India Ltd., New Delhi (2011): 223-228.