STUDIES TOWARD PRODUCING ECO-FRIENDLY PLASTICS

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ABSTRACT: Plastics have become a major factor in modern life and the massive volume of plastics in use has a significant effect on the environment. Major efforts are underway to reduce the impact of plastics on the environment and to make them more eco-friendly. Such efforts include the use of bio-materials instead of nonrenewable resources such as petroleum for manufacturing polymers. There are also studies which are aimed at reducing the impact of discarded plastic products on air and water supplies, as well as on flora, fauna, and landfills.

KEY WORDS: biodegradable plastics, starch, polyesters, polylactic acid (PLA), bio-based polymer, polyhydroxyalkanoates (PHA), biodegradation, aerobic degradation, anaerobic degradation, photodegradation, hydrolysis.

INTRODUCTION

POLYMERIC MATERIALS HAVE been widely accepted because of their ease of processability and amenability in providing a large variety of cost-effective products that help to enhance the comfort and quality of life in the modern industrial society. Over the years, the production of polymers has been growing rapidly in many applications, replacing conventional materials like wood, metal, and glass due to their advantages over these materials – these advantages include toughness, lighter weight, corrosion resistance, and easy processability that aids the manufacture of articles with various colors, complicated shapes, and designs.

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The varied types of polymers have led to widespread applications, such as commodity products (bags, electrical insulation, siding, roofing membranes, packaging, bottles, buckets, cabinets for TVs and computers, parts for washing machines, refrigerators and vacuum cleaners, etc.) and specialty products (made with conducting, photosensitive, liquid crystalline and bio-polymers for agricultural, aerospace, and electronics applications).

Polymers are broadly divided into thermoplastics and thermosets. Most thermoplastic materials can be recycled and reused until they are deteriorated enough to not have the required mechanical properties, at which time they need to be disposed of – preferably in an eco-friendly fashion. Thermosets, however, are completely cured and thus cannot be economically recycled or deteriorated for eco-friendly disposal. Accumulation of large amounts of waste material in nature is a core problem from an environmental point of view. Hence, there is an increasing demand to develop eco-friendly products. The term eco-friendly does not necessarily mean that the product needs to be completely biodegradable. It implies a product or technology which, when used or present in the environment, does not harm flora and fauna.

There are two main aspects of making polymers that are eco-friendly: (1) utilizing renewable resources to produce polymers (bio-based polymers) and (2) producing bio-degradable plastics. Many efforts are being made to combine these two aspects.

BIO-BASED POLYMERS

Plastics are almost exclusively made from a nonrenewable resource (petroleum), which also is the main source of energy for today's industrial world; hence with the rate at which petroleum is being consumed, there are fears of almost complete dry out in the next 60–80 years. Research and development is being carried out to synthesize polymers – such as lactic acid, caprolactone, and starch – from various renewable resources, especially from agricultural crops with the expectation that such bio-based polymers will be easier to fully degrade [1]. The problem in using biodegradable polymers like polyglycolic acid, polylactic acid (PLA), and polycaprolactone is that they do not have properties sufficient to fully replace common polymers [2,3]. For example, efforts have been made to improve polycaprolactone, which is a biodegradable polymer that has been used for years in drug delivery systems and food packaging, by blending clay nanocomposites in various proportions [4]. Although mechanical and thermal properties are improved by adding only a small amount of organically modified clay, further tests need to be carried out to determine if the properties of this plastic can be improved enough to be of practical use for a broad range of applications. Additionally, biodegradability tests will need to be conducted to verify that the new composition will eventually degrade naturally.

Several other new bio-based polymers are now being commercially developed with innovative new technologies and production methods. For example, PLA is made by breaking down the starch in corn, sugarcane, sweet potatoes, and other plants to produce glucose that is then fermented to produce lactic acid. This lactic acid can be polymerized and converted into PLA. These polymers also include a polyester family of compostable packaging material, which offers consumers good performance and cost effectiveness. Polyesters play a predominant role as a biodegradable plastic due to their hydrolysable ester bond. Commercially, biodegradable aliphatic polyesters being developed, e.g., polyhydroxyalkanoates (PHA) and PLA, are generally more biodegradable than aromatic polyesters; but they lack adequate mechanical properties for most applications.

Humans have long relied on biomass as the principal source of food, fuel, and fiber. Bio-based materials may indeed help reduce the dependence on nonrenewable energy and materials. However, these materials could result in increased reliance on agriculture as a source of industrial feed stock and might create conflicts with land needed for food production as well as increasing agricultural impacts on water and air quality. Thus, the major goal should be to utilize waste agricultural materials. Producing chemicals from most types of biomass is complicated by its heterogeneous composition, a mixture of simple sugars, sugar polymers, and more complex carbon compounds in the fibrous components of hemicellulose, cellulose, and lignins. Thus, one should be able to separate the different components of the biomass to produce a range of valuable products [5].

Bioresins initially costed two or three times as much as petroleum-based resins and often lacked the required strength and durability; but petroleum prices have been rising and bioresin makers have been getting more skilled at their trade, while increasing capacities and improving their goods performance so that these polymers are becoming economically attractive.

Naturally produced polyesters like PHA are actually synthesized by microbes, with the polymer accumulating in the microbe's cell during growth. This renewable-resource-based PHA has properties similar to polystyrene, which is used extensively in food packaging. Using plants (such as maize) as the basis for production is a sustainable solution but substantial energy consumption is required to obtain PHA. Nevertheless, Metabolix Inc. received the Green Chemistry 2005 Small Business Award from the US Environmental Protection Agency for its development of PHA and, in an alliance with Archer Daniels Midland Company, it has announced plans to build a plant of a capacity of 50 k tonnes/year in Iowa. The EPA reports that PHAs 'will biodegrade to harmless products in a wide variety of both aerobic and anaerobic environments' [6]. Industry ecology studies will be needed to provide insights into the impacts that a large scale transition to bio-based materials would have on nutrient flows in the environment.

Synthetic aliphatic polyesters, which are synthesized from diols and dicarboxylic acid via condensation polymerization, are known to be completely biodegradable in soil and water. Polyester-based families have recently been introduced by Cortec Corporation to bridge the gap between performance and biodegradability. In one example, it is achieved by incorporating various amounts of PLA so that the bio-based product (PLA-polyester blend) is biodegradable, with properties equivalent to that of HDPE [7]. The finished product also meets the standards of bio-based plastic products proposed by the United States Department of Agriculture.

The primary producer of PLA is NatureWorks LLC, which has started up a plant that can produce 140 k tonnes/year of PLA and has been supplying this material to other resin manufacturers while working with nine sheet producers and 11 film manufacturers to develop markets for this material which reportedly will decompose in 47 days [8,9]. It has had several adaptations for packaging of salads, fruits, and sandwiches; and in October 2005 it was announced that Wal-Mart, the world's largest retailer, had ordered over 100 M PLA containers. Toray Industries in early 2006 announced that it would build a plant to produce 5 k tonnes/year of PLA film in South Korea.

BIODEGRADABLE PLASTICS

Products made of biodegradable polymers must be stable during processing, storage, and use; but should then undergo degradation under environmental conditions when disposed in the waste stream after their use. They offer an alternative to traditional non-biodegradable polymers when recycling is not practical or economical. Basically, degradation means loss of properties. In the case of polymeric materials, loss of property occurs because of the change in assemblies of macromolecules or because of breakdown of macromolecules, or both. The breakdown of the macromolecules can be triggered by a chemical process, such as hydrolysis and oxidation, or by biological agents, such as microorganisms and related enzymes, or both. Degradation of by-products resulting from a simple chemical attack can be dispersed in the living environment without further interaction or can be inserted into other biological cycles to be converted into water and carbon dioxide.

The challenge posed to chemists and biochemists is to determine the extent to which the polymers are biodegradable. Many chemists, biochemists, polymer manufacturers, and independent testing groups have taken up this challenge. However, there is some disagreement as to what constitutes a biodegradable polymer. Polymer manufacturers are willing to accept the definition as a breakdown of a polymer structure into much smaller fragments that still contain the polymer. On the other hand, some environmentalists demand complete degradation into products usable by organisms. This would mean that when developing and designing polymers or plastics for degradation in the environment, the final stage should preferably be complete biodegradation and removal of any polymer from the environment. In this way, the polymer could be recycled through nature into microbial cells, plants, and animals, and, ultimately, back into chemical feedstocks. It has been proposed that an environmentally acceptable degradable plastic or polymer should be defined as one which degrades by photodegradation, oxidation, hydrolysis and/or biodegradation, while leaving no harmful residue in the environment [10].

The conflict between manufacturers and environmentalists has created the need for a standard system for determining the degree to which a polymer can undergo biodegradation. One proposed system includes measuring physicomechanical changes (changes in morphology and physical properties), chemical changes and products formed, and weight loss. A family of ASTM standards addresses degradation of plastics in a variety of specific environmental conditions including those in aerobic environments such as activated-sludge-wastewater-treatment systems (D5271), in soil or residual plastic material after composting (D5988), under controlled composting conditions (D5338), and a standard for assessing the compostability of environmentally degradable plastics (D6002) along with a standard specification for compostable plastics (D6400). Another group of ASTM standards addresses biodegradation of plastic materials in anaerobic environments such as municipal sewage sludge (D5210) under high-solids anaerobic-digestion conditions (D5511), and accelerated landfill conditions (D 5526). There are also ASTM standards for nonfloating biodegradable plastics in the marine environment (D7081) and for plastics that degrade in a combination of oxidation and biodegradation (D6954).

When comparing the degree to which different polymers biodegrade, several factors must be taken into consideration – one of which is the environment. Polymers may be tested in a natural or simulated environment. Simulated testing environments can be normal or accelerated. These are utilized to determine whether the polymer begins to degrade following disposal or while it is still in its intended use. The next aspect of biodegradable polymers which must be considered is polymer concentration. A polymeric product may have a high or low mass weight compared to its volume. In addition, there are wide variations in surface area to mass weight as the form of polymer ranges from a thin film to a thick building structure. (In most cases, a higher surface area to volume ratio will aid degradation; but for very thin films, it is frequently difficult to handle the film to obtain good degradation.) Finally, environmental effects of the polymer must be considered. A polymer that biodegrades is of little value if the products formed are found to contaminate water supplies or be toxic to living organisms in the environment.

The four main types of degradation are:

- Hydrodegradation
- Photodegradation
- Biodegradation
- Chemodegradation

Generally, the lower the molecular weight is, the easier it is to biodegrade a polymer. In many cases, long polymer chains must first be broken up by photodegradation or hydrolysis (hydrodegradation), and the actual transformation of these 'polymer links' is accomplished further by microbes. Compared with hydrolysis, photodegradation and bio-degradation which are the natural processes occurring in the environment, chemodegradation requires specific – and usually more expensive – chemical treatments for degradation (e.g., [11]). Additionally, the chemical approach requires selection of the material via a waste or recycle collection system, and it does not respond to the need for the degradation of litter. For these reasons, research is being focused more on photo, hydro, and biodegradation of polymers.

A truly degradable material is one that is degraded to carbon dioxide, water, and nontoxic minerals, leaving no environmentally harmful residues. Two closely linked mechanisms of degradation that are frequently confused with biodegradation are hydrodegradation (degradation via hydrolysis) and photodegradation

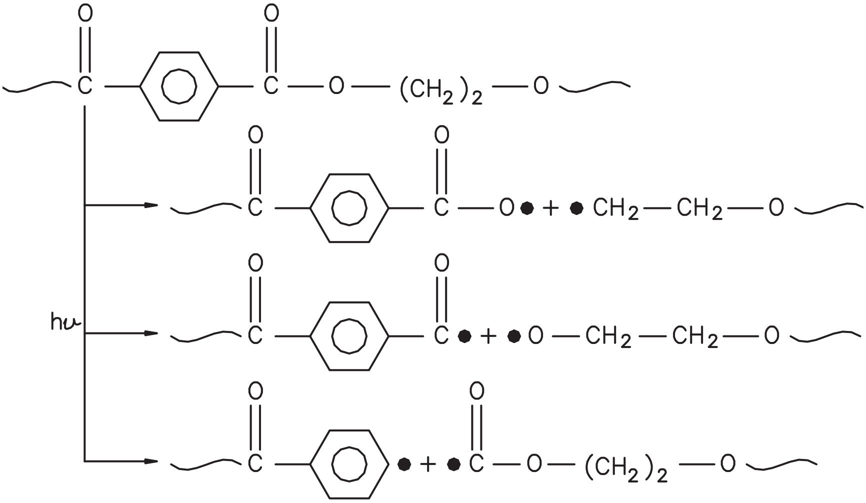
(degradation via photolysis). Since both mechanisms are often subsequently followed by microbial degradation, confusion of definition frequently occurs. Therefore, it has been proposed that a polymer whose degradation is initiated by hydrolysis or photolysis, and subsequently followed by microbial or enzymatic attack, should be termed as hydrobiodegradable or photobiodegradable, respectively.

Hydrodegradation: Usually called hydrolysis, is the reaction by which a molecule of water breaks a bond in the polymer. It is basically an exchange where one of the reactants is water and the other reactant is the compound being hydrolyzed. Polyesters and cellulosics are examples of polymers that are most subject to such attack. Cleavage of the ester bond, which occurs more readily under acidic or alkaline conditions, leads to lowering of molecular weight via the hydrolysis mechanism and later allows for further degradation by micro-organisms [12]. Many polymers are subject to hydrolysis and thermooxidative attack and thus additives are used to reduce such effects. In some uses, it would be possible to reduce the amount of such additives to result in a film that has adequate life for the desired use but that will decompose rapidly after that time.

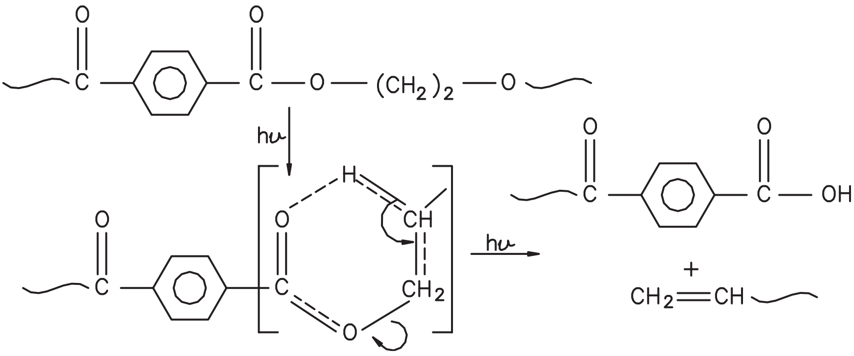
Photodegradation: This is especially important for the products that comprise litter on the ground or which float on water. Such litter is most objectionable since it is visible and sometimes causes problems for fauna. Here the degradation of polymer is by the action of ultraviolet light (UV) from the sun with a wavelength of 290–400 nm [13]. Most polymers do not have good UV stability and thus it is necessary to add carbon black, TiO_2, benzophenone, benzotriazole, HALS, and other stabilizers to provide adequate retention of properties during the expected life of the product. Therefore, with some polymers it may be possible to obtain the desired degradation by merely reducing or eliminating such additives.

To obtain adequate photodegradation, most polymers need to be modified during synthesis or post treatment to insert photochemically active groups. Addition of carbonyl functionality [14,15] into the polymer main chain or side chain, or of external photosensitizers and pro-oxidants such as metal salts [16–18], ketones, ethers, mercaptans, and polyunsaturated compounds [19] are examples that can lead to trigger a chain reaction that breaks the bond between the molecules. Degradation is evidenced by a decrease in molecular weight; the weight average molecular weight being inversely proportional to the amount of radiation received [20]. This lower molecular weight polymer is broken up into smaller particles by physical forces in the environment to a point where microorganisms are capable of transporting and metabolizing them.

When polymers are exposed to UV radiation, the activated ketone functionalities can fragment by two different mechanisms, known as Norrish types I and II. Degradation of polymers with carbonyl functionality in the backbone of the polymer results in chain cleavage by both mechanisms, but when the carbonyl group is in the polymer side chain, only Norrish type II degradation produces main chain scission [21,22]. Also, Norrish I reactions are independent of temperature effects and oxygen concentration at temperature above the T_g of the polymer [23].

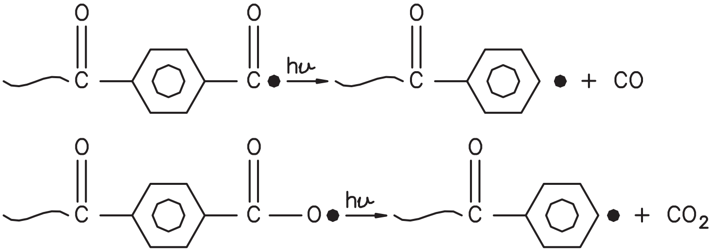


Scheme 1. Mechanism: Norrish type I.



Scheme 2. Mechanism: Norrish type II.

CO and CO_2 are produced by the reactions:



Once the photoactivator reduces the molecular weight down to about 9000, the polymer becomes biodegradable; e.g., by iron dithiocarbamate. In the weathering process with some polymers, thermooxidative degradation is the first step, eventually leading to photodegradation. The primary act in this process is a rupture of bonds of the macromolecules due to heat energy. Free radical sites are produced due to such cleavage of bonds. Subsequently, the radical sites react with the oxygen present in the air to form peroxy radicals. These radicals undergo chain scission to photodegrade by either the Norrish I or Norrish II mechanism discussed previously.

The rate of degradation depends not only on the type and amount of photodegradant present and the type of outdoor exposure, but also on the thickness of the plastic article, amount of pigment, other additives present, and type of polymer used.

Commercial pigments like ZnO, TiO_2, and CdS were examined for their influence on the photodegradation of ethylene–propylene copolymer. The polychromatic irradiation ($\lambda > 290$ nm) modified the course of photodegradation. This was evaluated by IR spectroscopy and hydroperoxide determination [24]. These tests showed that the presence of pigments can accelerate or retard the photodegradation depending on their photoactivity. The weathering of pigmented polymers and evaluation of the extent of photodegradation is important for two reasons; firstly to determine the initial photoproducts and secondly to assess the durability of the new pigment–polymer system. Lemaire et al. [25,26] studied the behavior of photoactive pigments in nonabsorbing polymers. A photoactive pigment acted as an inner screen for the photoproducts. Lacoste et al. [27] showed that the filler effect alone was observed at low concentrations and the photocatalytic influence was present only at higher concentrations. The build-up in the concentration of nonvolatile hydroperoxide showed IR absorption at 3400 cm^{-1} and was detected using the method of Petraj and Marchal [28], based on oxidation of Fe in solution with a ferrous ammonium thiocyanate solution. The ferric ammonium thiocyanate complex formed was spectrometrically titrated ($\lambda_{max} = 512.5\,nm$). The hydroperoxide concentration was calculated based on the stoichiometry.

TiO_2 was found to be a more efficient photocatalyst for hydroperoxide decomposition than ZnO [24]. Photochemistry of commercial pigments has been the subject of very extensive research in the photocatalyzed degradation and photostablization of polymers [29].

Biodegradation: Biodegradable polymers constitute a loosely defined family of polymers that are designed to be degraded by living organisms such as bacteria and fungi. They offer a possible alternative to traditional nonbiodegradable polymers when recycling is impractical or not economical. The main driving force behind this technology is the solid waste problem – particularly with regard to the decreasing availability of landfills, the litter problem, and pollution of the marine environment by nondegradable plastics.

Biodegradable polymers are capable of being chemically transformed by the action of biological enzymes or microorganisms into products which themselves are capable of further biodegradation. By-products of degradation can be dispersed in the living environment without further interaction or can be inserted into biological cycles to be converted into water and carbon dioxide.

The long chain molecular structures of polymers make it difficult for the enzymes of bacteria and fungi to digest the molecular structure. Moreover, the semicrystalline structure of many plastics means that the entry of water/moisture and enzymes into the polymer matrix is restricted.

Most synthetic polymers are hydrophobic and hence do not absorb moisture, which is necessary for the existence of most bacteria to cause biodegradation. Attempts to develop new biodegradable polymers have centered mainly on the following areas: synthesis of novel biodegradable backbones, and developing biodegradable polymer composites and blends.

(a) Heterochain polymers are relatively more susceptible to enzymatic attack than carbon–carbon chain polymers. It is proposed that the chain containing polar and hydrolyzable groups in the backbone would be attacked in a random fashion to reduce the molecular weight more efficiently than by oxidation at the chain end. This reduction in molecular weight should enhance biodegradability.

If various biodegradable links such as amide and ester bonds or units such as amino acid or blocks such as peptide are incorporated in the polymer backbone, then they serve as starters to initiate enzymatic hydrolysis.

Hydrophobic polymers usually cannot be attacked by microorganisms. To make such polymers biodegradable, fillers such as starch, cellulose, lignin etc., are added to the polymers. For example, starch is added to the polymers because some microorganisms utilize the starch as a nutrient source and secrete enzymes to break it down for consumption. These enzymes can then act on the polymer, provided the polymer can be broken down by them.

(b) Starch is a form of polysaccharide, which is used by plants to store energy. Starch exists in two different configurations:

1. Amylose – which is in the form of a linear chain.
2. Amylopectin – which is in the form of a highly branched chain.

Many starches have both configurations and, depending on the plant source, the two forms are present in different ratios. Amylose contributes to the gelling property of starch, whereas amylopectin contributes to higher viscosity. Both properties are important in the preparation of food; and the ratios may be important in the degradation of starches.

Starch is added to polymers in two basic ways. The first method of starch addition is the attachment of acrylic acid segments at various locations on the polymer chain. The acrylic acid segments form a hydrogen bond with starch. The second method of adding starch is to graft a polyethylene molecule to a starch molecule. This grafted molecule reacts readily with the pure polyethylene and starch to produce a copolymer.

Cellulose can also be added to a polymer to make it biodegradable. As the main constituent in any natural fiber (up to 60–80%), cellulose is a cell wall forming substance, which is vulnerable to microbial attack. It influences degradation of the resin matrix by altering the morphology. The elementary unit of cellulose is α-D glucose. This contains three alcoholic groups, which form strong internal hydrogen bonds within the macromolecules and also with hydroxyl groups of other molecules. Due to the presence of these hydroxyl groups, vegetable fibers are extremely hydrophilic. This hydrogen bonding causes fiber bunching and poor dispersion of fiber in the matrix. Although the hydrophobic polymer matrix prevents wetting of the fibers, good fiber–resin interaction can elevate the fiber from being fillers to the level of reinforcement. Various techniques have evolved to improve such interaction and more are being developed.

Proper compounding can frequently overcome the hydrophobic problem through the use of coupling agents, which contain organic as well as inorganic groups, to bridge the gap between resin and reinforcement. For example, organofunctional silanes have alkyl groups that form covalent bonds with the resin, and also have hydroxyl groups that bond with the reinforcement. Another such coupling agent is AIBN (azo-bis-iso-butyronitrile).

Coupling agents eliminate weak boundary layers and provide a tough and flexible layer at the boundary interface. They develop a highly cross-linked interface region with an intermediate modulus. These agents form covalent bonds between both materials; and by altering the acidity of the substrate surface, they produce an acid–base interaction between the fiber and the resin. Coupling agents also improve the wettability of natural fiber by the polymer and reduce the moisture regain tendency of natural fiber.

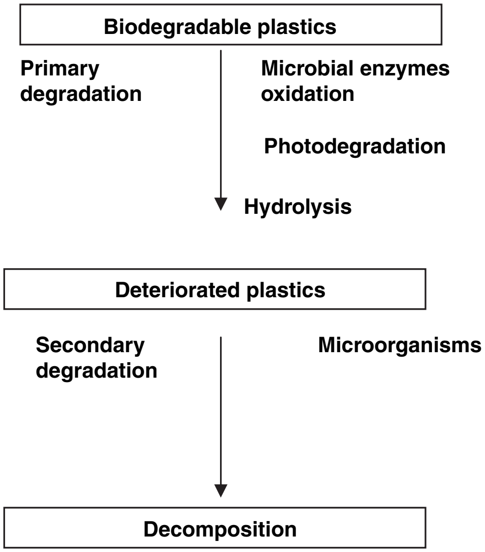
Expensive coupling agents can lead to economic unfeasibility of the composite system. Compatibilizers, on the other hand, can be cheaper and yet provide good resin–fiber interaction, although they do not result in cross-linking. Compatibilizers work by bridging the gap between a hydrophilic and hydrophobic space. Therefore, when block or graft co-polymers are used as compatibilizers, they must have hydrophobic and hydrophilic components. These compatibilizers are essentially copolymers, which are surface active coupling agents that bind natural fiber to the hydrophobic polymer matrix; examples include 12-hydroxy stearic acid (12HSA) and polystyrene/acrylic acid.

Once a composite of a blend of polymer system is prepared, the breakdown is caused by the following mechanisms:

1. A biophysical effect, in which cell growth can cause mechanical damage, e.g., starch molecules absorb water so the molecular structure gets stretched and the surface of the polymer develops cracks and ruptures.
2. Direct enzymatic action, in which enzymes from the microorganisms attack the components of the plastic product leading to splitting or oxidative breakdown of the plastic product under appropriate conditions of moisture, temperature, and oxygen.

All naturally occurring polymers, such as starch, cellulose, and proteins, can be utilized as food for microorganisms. These can be added into the polymer matrix to achieve biodegradable polymers [30].

The biodegradation of plastic and any incorporated additives will take place in two steps or phases.



As shown in the figure, the initial phase results in a deteriorated plastic, by virtue of biodegradation of one of the components of the plastic through the action of environmental stresses such as hydrolysis, oxidation, or UV light. The deteriorated plastic can then be biodegraded only if the deterioration is sufficient to cause a decrease in molecular weight to a point where the microorganisms are capable of transporting and metabolizing the polymer fragments. The second phase or series of events results in actual biodegradation or decomposition of the material.

Much research is being carried out at present on blending starch or jute along with different coupling agents to produce a biodegradable polymer [1]. The methods for the incorporation of natural fibers into polymer matrix are *solution blending* or *melt blending*. By obtaining a uniform dispersion of fiber, one can achieve a good fiber–resin interaction which gives a breakdown of the polymer matrix by reduction in molecular weight when exposed to biodegradation.

Tests on biodegradable polymer films have been carried out in aerobic and anaerobic environments. For example, Krupp and Jewell at Cornell University conducted aerobic and anaerobic biodegradation tests on thin films of 12 polymers with varying amounts of starch that were claimed to be biodegradable by their respective manufacturers in 1989. However, they found only one of these plastic films to be fully biodegradable [30].

The biodegradation that occurs is characterized by total carbon conservation. For the aerobic environment, the carbon equation is given by:

$$C_t = CO_2 + H_2O + C_r + C_b$$

where C_t is the total carbon contained in the polymer. Following biodegradation, the carbon from the polymer will appear in one of three end products: CO_2 which is a product of the respiration of the microorganisms; C_r which is any residue of the polymer that is left or any by-product that is formed; and C_b which is the biomass produced by microorganisms through reproduction and growth.

For the anaerobic environment, the total carbon equation is:

$$C_t = CO_2 + CH_4 + H_2O + C_r + C_b$$

where C_t, C_r, and C_b represent the same forms of carbon as mentioned previously. However, since atmospheric oxygen is not present, methane is a possible product of anaerobic degradation.

There have been numerous communications on the subject of biodegradation test methods, including aerobic compost [31], anaerobic bioreactor [32], future directions [33,34], and a fine review article [35]. Despite the fact that biodegradation testing until the late 1980s had not been adequately standardized and interpretations of many reported data in the literature are thus questionable, some guidelines based on the polymer structure, polymer physical properties, and environmental conditions at the exposure site have emerged for predicting the biodegradability of synthetic polymers [36–38]. In considering the polymer structure, the following generalizations can be made concerning biodegradation:

- A higher hydrophilic/hydrophobic ratio is better for biodegradation.
- Carbon chain polymers are unlikely to undergo biodegradation.
- Condensation polymers are more likely to undergo biodegradation.
- Low molecular weight polymers are more susceptible to biodegradation.
- Crystallinity slows down biodegradation.

ECM BioFilms, Inc. recently developed a ‘one percent additive technology’ for the manufacture of biodegradable plastic products [39]. These additives are being manufactured and sold for polyolefin packaging products; research is being done on development of other additives based on the same technology for use in other plastic resins such as polystyrene. ECM claims that it thus has the least expensive and most widely applicable technology for making plastic products biodegradable while maintaining their other desired properties.

This biodegradation process can take place aerobically and anaerobically. It can take place with or without the presence of light. This technology enables the microorganisms in the environment to metabolize the molecular structure of plastic films into a humus form that can be further metabolized and eventually rendered as water, gas, and minerals that are beneficial to the environment and conducive to plant growth. The company’s process is a proprietary formulation that is mixed with carrier resins to make masterbatch pellets that can then be added to plastic resins. Plastics manufactured with these additives will fully biodegrade in home compost heaps and in commercial composting operations (both in high heat and in low heat [vermiculture] processes); in addition, they will degrade when buried in the ground, buried in landfills, tilled into the soil, or merely tossed out as litter.

CONCLUSIONS

Increasing demand for bioplastics has resulted in international corporations expanding their development and production of these materials. It can be stated that bio-friendly polymers are now a reality, based on the information found. Natural polymers or synthetic polymers based on naturally occurring monomers appear to be the best area for future development. These bio-based polymers usually lack some of the properties that have made synthetic polymers so popular – such as water resistance, excellent physical properties, and relatively low cost – but dramatic improvements have been made. Bio-based materials may indeed help reduce dependence on oil and other nonrenewable materials; but research must continue on the impacts of their production, use, and disposal as well as their impact on nutrient flows in the environment.

Taking into consideration the different techniques involved in preparation of biodegradable polymers, it appears advisable to look at the molecular structure of the polymer to find out whether the backbone chain has sites for photodegradation. If not, photoactivators, such as iron dithiocarbamate, maleic anhydride, ketones, and carboxylic group based additives, can be added along with organic fillers like starch, cellulose, or lignin. These additions should ensure the initiation of degradation through decrease in molecular weight.

In attempts to make the polymer biodegradable, care has to be taken so that the percentages and types of filler and additives are added in such proportions so as not to unduly deteriorate the properties of the virgin polymer during its projected period of use. There are a wide range of opportunities for trying various combinations and proportions of fillers and additives so as to retain the properties of a polymer and also make it biodegradable. New technologies emerging to make polymers biodegradable, e.g., PLA-polyester blends or 1% additives in polyolefin, have given further scope for invention along similar lines. With the expanding global demand for environmentally friendly products, bioplastics will certainly become an important contributor to 21st century's Green Revolution.

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