Overview of biodegradable polymers and solid-waste issues

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ABSTRACT: Plastics are a major component of the solid-waste disposal stream in the United States. There are three categories of degradation technology for plastics. Procedures for determining the effectiveness of these technologies and specific criteria to aid in the selection of a particular degradation system for a given product application are under development.

KEYWORDS: Biodegradability, degradation, evaluation, municipal wastes, plastics, polymers, solid wastes.

The durable properties of plastics make them the material of choice for a large number of varied applications ranging from packaging to toys. A consequence of this phenomenal utilization of plastic materials is their high visibility. This makes them a major focal point in the controversy over the growing solid-waste disposal problem in the United States.

Plastics and solid-waste issues

Litter and municipal solid waste

The fundamental solid-waste issues today comprise the areas of increasing litter and increasing municipal solid waste. Plastic litter is often especially newsworthy because of reported wildlife deaths by entanglement and ingestion of discarded plastic articles. This plastic litter is not the biggest problem of the solid-waste issue, however. Municipal solid waste is the problem. In the last 30 years, Americans have increased their yearly output of trash from 176 billion pounds to over 360 billion pounds. This is an average of nearly 1500 pounds of trash per year for every man, woman, and child in the United States. The bill for handling this much garbage is currently about 15 billion dollars per year. The 73% majority of this waste goes into landfills. Another 14% undergoes incineration and 13% recycling. Landfills, especially in urban areas, are therefore filling at an alarming pace. Today there are only about 5500 active landfills in the United States. It is difficult to site new landfills because of stricter EPA rules; the high cost of more than US$ 1,000,000 an acre to construct new, safe landfills; and the dislike of the general public for a landfill situated nearby.

Coupled with the growing concern over the burgeoning municipal waste disposal problem is the increasingly genuine desire for the conservation of natural resources. Are we throwing away valuable resources in our garbage? Have we gone too far with the so called "throw away mentality?" Many people today answer these two questions with a resounding "yes!"

Plastics in solid waste

How much of the solid-waste problem is really due to plastic waste? Because plastics are a high profile item in garbage, there is apparently a public perception that plastic is the major contributor to the landfill congestion problem. Certainly this country produces much plastic. In 1991, domestic manufacturers produced over 50 billion pounds of plastics.

How much does plastic contribute to the municipal solid waste stream? Typical estimates which are shown in **Fig. 1** suggest that plastics represent about 20% by volume of the solid waste of an average city. By comparison, paper accounts for about 34% by volume. Examining municipal solid waste from a weight basis and a packaging and container viewpoint, plastics comprise an estimated 8%. Paper is approximately 14%, metal 4%, and glass 2% of all packaging and container material in municipal solid waste. **Figure 2** shows these values graphically.

What have researchers found when they excavated landfills that have been in use for 20 or 30 years? William Rathje, a professor at the University of Arizona, has been studying landfills for over 17 years. Using a bucket auger Rathje has been able to dig down 100 ft into landfills and obtain samples of trash over 20 years old. He found that plastics were only 10% of the volume of an established landfill. Rathje has suggested that this low volume of plastics compared to the estimates of plastics in municipal solid waste is

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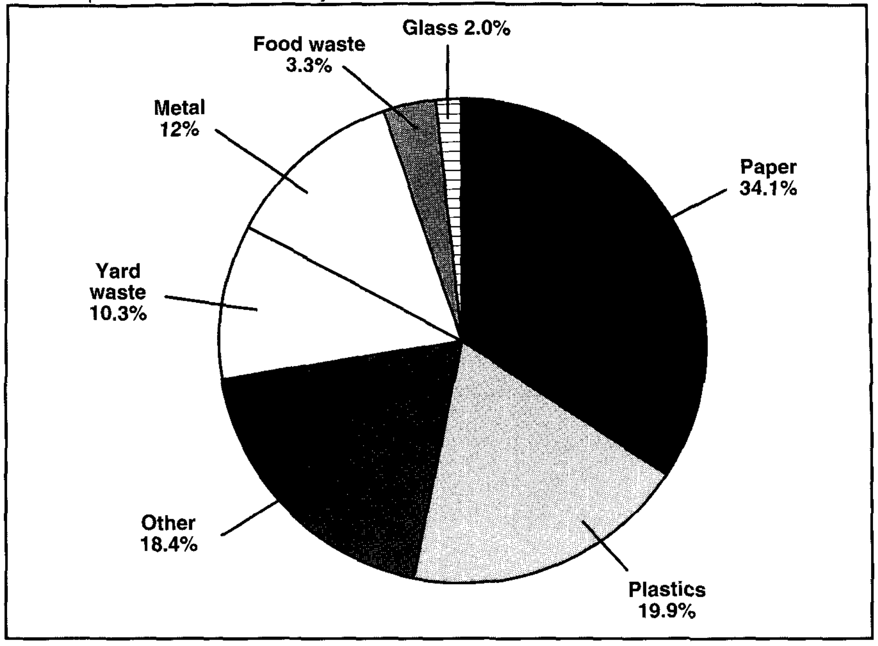
probably because most plastic articles are highly crushable and, therefore, compact very effectively in the landfill environment.

Rathje also found that the percentage of plastics in the average landfill has not significantly changed from the early 1970s to the late 1980s. This is an interesting observation considering that the general use of plastics has increased significantly during this period. Rathje believes that the level of plastics is constant because of "light weighting." This is a form of source reduction by which converters and packagers achieve improved cost efficiency by producing packaging and containers with lower levels of plastic material.

The major component of a landfill according to Rathje is paper. Paper has grown from 30% by volume in 1970 to 50% by volume today. It is therefore quite likely that plastics are not the primary problem in landfills. Nevertheless, they are certainly a part of the problem of municipal solid waste and deserve attention accordingly.

1. Municipal solid-waste content by volume



Potential solutions to solid-waste problems

Over the last five years, there have been a number of proposed solutions concerning the best ways to deal with the solid-waste crisis. These generally fall into the following categories:

- Source reduction
- Recycling
- Waste to energy incineration
- Landfilling
- Education
- Composting
- Degradable plastics.

The first four items comprise the Environmental Protection Agency's (EPA) "Four Point Approach." The essential idea is to minimize landfilling by better using source reduction, recycling, and incineration.

Education is probably a component of all lists of solutions. It is essential to educate the public on the realities of garbage and the tradeoffs and consequences of various options available for dealing with the solid-waste crisis.

Composting may offer a significant addition to the EPA's four point approach. Yard waste, food waste, paper and other organic matter comprise an estimated 60% of municipal solid waste that goes into a landfill. These are candidates for composting. Complete composting of suitable municipal solid waste occurs in a relatively short time under proper conditions. Although there are now only 19 solid-waste composting plants in the United States, an additional 150 plants in 30 states are under development. Composting is not part of the degradable category discussed here because it is more than a degradable system. It is more typically a type of "recycle system" because a resource—compost—results.

One recommended solution is to make plastics degrade at an accelerated pace after they have been discarded. Evidently the early reasoning for this proposed solution was that accelerated degradation of plastics would reduce the likelihood of wildlife entangling or ingesting littered plastic articles such as beverage loop carriers and bags. Additionally, landfill capacities might be enhanced, if plastics degraded faster. The first reason has merit. For several years, companies have now been producing photodegradable plastic articles that will degrade at accelerated rates when littered.

The second reason is more controversial. It is a fact that most plastics do not degrade in current landfills. At least they do not degrade at a rate that would make a significant difference. Questions arose, however, whether degradable plastics would decompose fast enough to make a meaningful difference in landfill capacity. If degradable plastics did work, would they cause more problems than they cured by adding to the production of leachate? After all, landfill leachate contamination of groundwater systems is a major reason why many landfills have been closed.

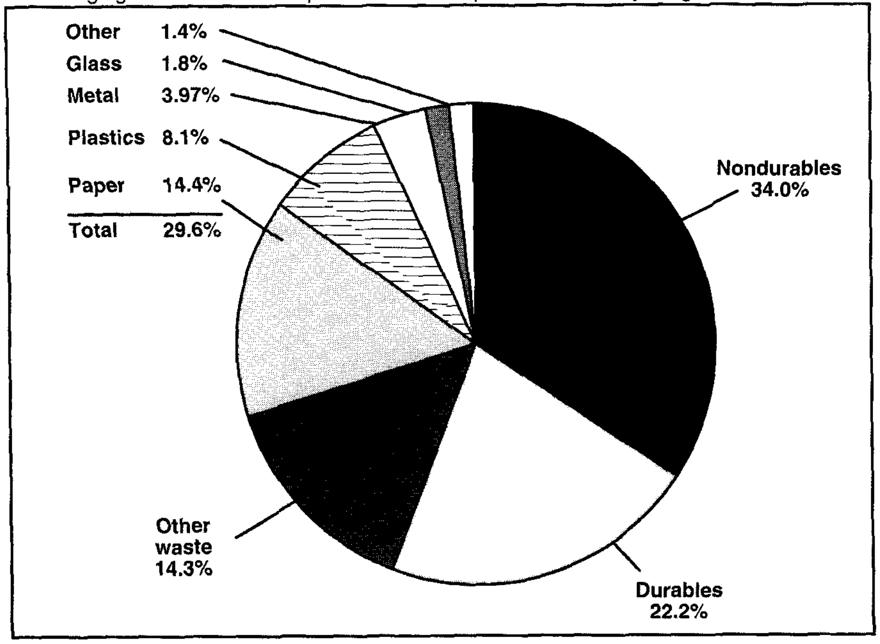
Degradation technologies

There are 3 categories of degradation technology for plastic:

- Photodegradation
- Chemical degradation
- Biodegradation.

All of the following degradation definitions are simple ones which are meant

2. Packaging and container components of municipal solid-waste by weight



to express something of the nature of the primary ways in which environmental degradation occurs. The American Society for Testing and Materials (ASTM) Subcommittee D-20.96 has more explicit technical definitions for types of degradation.

Photodegradation

Photodegradation is degradation resulting from the action of sunlight. More specifically, certain wave lengths of UV light cause the breakdown and fragmentation of most plastics. Plastics contain trace impurities such as iron compounds, catalyst residues, and some oxidation products from their manufacture and fabrication. These impurities can absorb UV light to produce free radicals which then attack the molecular chains of the plastic and cause a breakdown.

Photochemical degradation is the primary way that most plastics degrade in the environment. Most polyethylene and polypropylene materials for outdoor applications contain stabilizers to retard the destructive effects of UV light. Unstabilized 2.5-mil thick films of polyethylene have been fragmented in less than 90 days of outdoor exposure during a Texas summer.

Chemical degradation

Chemical degradation occurs when a plastic breaks down primarily by oxidative means. For example, the presence of certain impurities such as iron can catalyze the photo-oxidative and thermal oxidative degradation of polyethylene. Such materials are pro-oxidants. Chemical degradation can also include other chemical chain scission reactions such as hydrolysis, provided there are functional groups in the polymer chain that will undergo such reactions.

Biodegradation

Biodegradation results from the actions of microorganisms in the environment. Since polyethylene and similar plastics are relatively new substances composed of very long, water insoluble, hydrocarbon molecules, no naturally occurring strains of microbes have yet evolved that are able to assimilate rapidly these materials. Of course, the imperviousness of plastic to microbial attack is one of its extremely favorable attributes and a primary reason why it is used extensively in food packaging and storage.

A special type of biodegradation that has been receiving considerable attention lately is composting. Composting is dependent on aerobic biodegradation. As mentioned earlier, composting can generate a useful product.

Biodegradation systems

It is possible to induce biodegradation in many plastic materials by one of two primary methods:

- Fragment long molecular chains to pieces small enough for microbe assimilation.
- Develop polymers with biodegradable molecular chains or components.

Pro-oxidants

As noted above, pro-oxidants cause fragmentation or chemical degradation. Additives containing pro-oxidants may be both photo- and thermally activated. Examples of these types of systems are those containing transition metals such as cobalt, iron, manganese, etc. If there are sufficient oxygen and heat, these pro-oxidants will catalyze the oxidative degradation of a polymer such as polyethylene causing fragmentation. Some starch-based biodegradation additives also use pro-oxidants.

Oxygen containing compounds

Other additives that can produce fragmentation are oxygen containing compounds. An example is the ethylene carbon monoxide copolymer which contains very photosensitive ketonic carbonyl groups (C=O). The ethylene carbon monoxide copolymers made by a number of suppliers function as stand-alone systems, because their effectiveness is drastically reduced in blends with noncarbonyl containing polymers. Such systems require appropriate exposure to UV light before they are sufficiently fragmented for microbe assimilation. The ethylene carbon monoxide copolymers are currently being used to produce photodegradable beverage loop carriers.

Water soluble polymers

Another type of fragmentation or dissolution of polymer molecular chains occurs with certain polymers in appropriate aqueous environments. The polyvinyl alcohols are one example of a hydrolyzable polymer which is commercially available. Reports indicate that they are also biodegradable, repulpable, and compostable.

There are two other water soluble systems in the marketplace which have often been categorized as degradable, although they are primarily designed as "recoverable and reusable" type systems. One system contains polyethylene oxide and a compatible polymer. It is soluble in cold or cool water and designed for recovery and reuse of its constituent polymer. The system is also photodegradable, if discarded in the environment. Another system primarily designed for recovery and reuse is an acrylic polymer available from one supplier. This polymer is soluble in alkaline solutions.

Polymers with microbe degradable chains or components

Some polymeric systems are biodegradable because they either possess degradable functional groups such as esters, lactones, urethanes, or similar entities in the polymer chain or they are blends or grafts with biodegradable materials such as starches. Biodegradable polymeric systems fall into two main groups, the "new wave" starch-based polymeric systems and the nonstarch-based systems.

The starch-based polymeric systems are more like conventional thermoplastics because they are not additives. Instead, they are stand-alone systems which can be fabricated into films, containers, etc. Most appear to contain significantly higher levels of starch than earlier starch-based systems. Commercially available systems may use 60% starch, 60–98% starch, or starch and polyurethane.

Nonstarch-based systems which are biodegradable include a lactic acid polymer, a polycaprolactone, and a polyhydroxybutrate valerate.

Biodegradation of plastics in municipal solid-waste

Landfills

The question arises regarding how well plastic biodegradation systems work in the landfill. The research by Rathje offers a probable answer to this question. His studies indicated that little, if any, rapid biodegradation occurs in the average landfill. He found many types of organic waste materials which should have been significantly biodegraded but were not. For example, in the late 1980s, he found a landfill contained recognizable corn on the cob that had been discarded in 1971.

Current EPA mandates require layering and sealing of the typical landfill in such a manner that very little air or moisture are present. This significantly retards biodegradation. In discussing landfills, James Noble of Tufts University Center for Environmental Management stated, "It is not surprising that everything doesn't biodegrade rapidly; the miracle is that anything biodegrades at all."

For most biodegradation additives or biodegradable plastics to degrade at a rapid rate, it is necessary that air and moisture are present. In addition, the pro-oxidant systems require certain levels of oxygen to function effectively. If there is insufficient air and moisture present in the typical landfill to biodegrade common food waste rapidly, one would generally not expect a given plastic biodegradation system to degrade very effectively either.

Compost systems

Unlike the typical sealed, tomb-like landfills, compost systems function primarily by the activities of aerobic microbes. Any plastic biodegradation system that degrades fairly rapidly by aerobic microbes may be a suitable candidate for testing in a municipal compost plant. Currently there are considerable efforts led primarily by a large consumer products supplier to use compostable plastic systems on a large scale.

Key considerations concerning degradable plastics

Certainly one should investigate thoroughly any candidate which is claimed to be a degradable system. There are, however, some initial questions before determining the technical efficacy for a given system. First it is necessary to know whether degradation is the appropriate solution to a product's apparent impact on solid-waste problems. Would another solution be more appropriate? Recycling, source reduction, education, or combinations thereof may be preferable options for many cases. A very important point to consider is that designing a product to degrade (with the exception of composting) may preclude its being used as a possible resource. In other words, if the product is degraded, it often cannot be recycled or its energy recovered through incineration.

Another question concerns what by-products, if any, might occur during the degradation system for a particular application as it undergoes decomposition. Is there a possibility of adverse effects on plants, animal life, or humans? For example, will a given biodegradation system form toxic materials in a landfill or a compost windrow? One of the goals of the ASTM Institute for Standards Research is to determine testing procedures which will allow the determination of the ultimate fate of degradable materials in various environments.

Will the degradation system adversely affect any of the performance properties of a product in the pre-degradation stage? Will there be a compromise in strength or an adverse effect on taste and odor? Would the bacterial growth which one normally tries to inhibit in many plastics packaging applications be encouraged in the performance phase?

Will the degradation system adversely affect the processing or fabrication of the product? Will the degradable systems require new operating conditions and possibly more expensive processing equipment?

Finally, will the addition of the degradation system significantly hinder recycling of any waste stream that might contain the product?

Evaluation of effectiveness of degradable systems

Once the decision is made to use a degradable system, it is necessary to determine its effectiveness. One must know if the degradation system will cause the application to degrade within a reasonable or designated time. Obviously the best way to know this is to test the degradable system for the application in the waste environment in which it will be discarded. It is possible to develop testing based on knowledge of the typical exposure environments and the rate of degradation required. Alternatively one can use a standard procedure now being developed by the ASTM. This organization has undertaken the arduous and complex task of standardizing testing for degradable plastics. Specifically, the D-20.96, Environmentally Degradable Plastics Subcommittee, is developing standard tests and classifications for degradable plastics. They are focusing on the development of two primary areas. One pertains to standardizing both natural and laboratory exposure environments. The other concerns the development of standard testing that will allow the determination of a degradation end point or the degree to which an article has been degraded with time in a certain exposure environment. This latter item usually involves the periodic measurement of a physical property to determine how much it has deteriorated upon exposure to the environment. For example, after exposing a plastic film to sunlight for a given period, one can measure the tensile strength of the film and determine how much it has decreased from its former level. The end point is the time at which the plastic article has reached a certain state of decay. An end point can be the time at which the tensile elongation of a plastic film has decreased to an absolute 5% or less.

The ASTM D-20.96 subcommittee contains six sections each of which focuses on some aspect of plastics' degradability. The biodegradation section has established two standard methods: D-5209-91, Measure for determining aerobic biodegradation of plastic materials in presence of sewer sludge, and D-5210-91, Measure for determining anaerobic biodegradation of plastic materials in presence of sewer sludge. This section is currently developing 10 other procedures involving controlled laboratory environments which simulate natural environments such as landfill, compost, marine water, fresh water, specific microbe, soil exposure, and activated sludge.

The photodegradation section of D-20.96 has established three standard practices: D-5071-91, Practice for operating a xenon arc type exposure apparatus with water for exposure of photodegradable plastics; D-5208-91, Practice for operating fluoroscent UV and condensation apparatus for exposure of photodegradable plastics; and D-3826-91, Practice for determination of degradation end point in polyethylene/polypropylene (films) using tensile test. The first two practices provide procedures for exposing degradable plastics to UV light and the other procedure shows how to measure the degradation end point. Other practices are being developed in artificial and natural exposure systems which involve polyethylene and polystyrene.

The chemical degradation section of D-20.96 is developing a practice that will allow testing the effectiveness of chemical degradation systems such as the transition metals.

The concern of the environmental fate section is what happens to the degrading system in the environment. For example, they are considering the fate of toxic chemicals or metals released during the degradation process. This section has established one procedure, D-5152-92, Practice for water extraction of residual solids from degraded plastics for toxicity testing.

The terminology section is one of the most complex areas. Nevertheless, they have developed precise terminology that couples succinct technological definitions with references to appropriately supportive ASTM practices and tests. The terminology definitions have been published by D-883.

The classification section is in the process of developing a simple but descriptive labeling system for degradable applications and establishing a classification system that allows the categorization of the relative effectiveness of the degradable system in both natural and laboratory environments. The ASTM Institute for Standards Research is coordinating a program to correlate laboratory and field degradation results.

Support of the ASTM is vital in establishing these standard procedures which should provide a rational framework from which the public, industry, and government can make technologically sound decisions concerning the optimum utilization of degradable plastics.

Conclusions

Degradable systems may be a viable solution for some plastic articles which are litter prone, not easily collected, or present a significant hazard to wildlife through entanglement or ingestion.

In considering the use of a degradable system, one should determine if a significant resource is lost by degradation. Thus it is necessary to determine if the plastic could be better used through recycling or incinerating. For example, a potentially better type of degradation for municipal waste may be composting, since it does produce a useful resource.

Finally, it is especially important to evaluate thoroughly any degradable system by the best available procedures to determine its potential effect on the environment and its actual ability to degrade within a reasonable period in a given waste environment.

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