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Biodegradable Polymers: Past, Present, and Future

M. Kolybaba¹, L.G. Tabil¹, S. Panigrahi¹, W.J. Crerar¹, T. Powell¹, B. Wang¹

¹Department of Agricultural and Bioresource Engineering

University of Saskatchewan

57 Campus Drive, Saskatoon, SK, CANADA S7N 5A9

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Abstract. *In recent years, there has been a marked increase in interest in biodegradable materials for use in packaging, agriculture, medicine, and other areas. In particular, biodegradable polymer materials (known as biocomposites) are of interest. Polymers form the backbones of plastic materials, and are continually being employed in an expanding range of areas. As a result, many researchers are investing time into modifying traditional materials to make them more user-friendly, and into designing novel polymer composites out of naturally occurring materials. A number of biological materials may be incorporated into biodegradable polymer materials, with the most common being starch and fiber extracted from various types of plants. The belief is that biodegradable polymer materials will reduce the need for synthetic polymer production (thus reducing pollution) at a low cost, thereby producing a positive effect both environmentally and economically. This paper is intended to provide a brief outline of work that is under way in the area of biodegradable polymer research and development, the scientific theory behind these materials, areas in which this research is being applied, and future work that awaits.*

Keywords. biopolymer, biodegradable, plastic, agricultural products, biomaterial, recycling, life cycle assessment, environmental impact, economic impact, compost

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Introduction

The development of innovative biopolymer materials has been underway for a number of years, and continues to be an area of interest for many scientists. In 1996, shipments from the Canadian Plastic Industry increased by 10.6% from 1995 levels (Charron 1999), to \$9.1 billion. Fomin (2001) reported that the end of the 20th century saw the worldwide production of synthetic plastics reach 130 million t/year, while the demand for biodegradable plastics is reported to be growing by 30% each year (Leaversuch 2002). European countries have reported an estimated average usage of 100kg of plastic per person each year (Mulder 1998).

Synthetic plastics are resistant to degradation, and consequently their disposal is fuelling an international drive for the development of biodegradable polymers. As the development of these materials continues, industry must find novel applications for them. Material usage and final mode of biodegradation are dependent on the composition and processing method employed. An integrated waste management system may be necessary in order to efficiently use, recycle, and dispose of biopolymer materials (Subramanian 2000). Reduction in the consumption of sources, reuse of existing materials, and recycling of discarded materials must all be considered.

Polymer materials are solid, non-metallic compounds of high molecular weights. (Callister 2000). They are comprised of repeating macromolecules, and have varying characteristics depending upon their composition. Each macromolecule that comprises a polymeric material is known as a mer unit. A single mer is called a monomer, while repeating mer units are known as polymers. A variety of materials (both renewable and non-renewable) are employed as feedstock sources for modern plastic materials. Plastics that are formed from non-renewable feedstocks are generally petroleum-based, and reinforced by glass or carbon fibers (Williams et al. 2000). Renewable resource feedstocks include microbially-grown polymers and those extracted from starch. It is possible to reinforce such materials with natural fibers, from plants such as flax, jute, hemp, and other cellulose sources (Bismarck et al. 2002).

Economic concerns must be addressed objectively as biopolymer materials are developed, because the future of each product is dependent on its cost competitiveness, and society's ability to pay for it. Many governments are introducing initiatives designed to encourage research and development of biologically based polymers. Most European and North American politicians and policy makers support work in this area, with the German government being particularly interested (Grigat et al. 1998).

The future outlook for advancement in the area of biodegradable plastics is ultimately promising. Canada's biotechnology infrastructure is world class, with the provinces of Ontario, Quebec, and Saskatchewan being particularly active and successful in research and development. Crawford (2001) explained that Canada's long term goal on the international front is to develop technologies that are able to accept a diverse combination of raw materials, and produce multiple outputs, while releasing no emissions.

This literature review is intended to provide information regarding progress made in the development of biodegradable polymer materials. Biodegradability, constituent materials, applications, methods of biodegradation and environmental and economic implications of such materials will be examined. Finally, information regarding the future direction for biodegradable polymers will be objectively discussed.

BIODEGRADABILITY OF POLYMERS

The American Society for Testing of Materials (ASTM) and the International Standards Organization (ISO) define degradable plastics as those which undergo a significant change in chemical structure under specific environmental conditions. These changes result in a loss of physical and mechanical properties, as measured by standard methods. Biodegradable plastics undergo degradation from the action of naturally occurring microorganisms such as bacteria, fungi, and algae. Plastics may also be designated as photodegradable, oxidatively degradable, hydrolytically degradable, or those which may be composted. Between October 1990 and June 1992, confusion as to the true definition of "biodegradable" led to lawsuits regarding misleading and deceitful environmental advertising (Narayan et al. 1999). Thus, it became evident to the ASTM and ISO that common test methods and protocols for degradable plastics were needed.

There are three primary classes of polymer materials which material scientists are currently focusing on. These polymer materials are usually referred to in the general class of plastics by consumers and industry. Their design is often that of a composite, where a polymer matrix (plastic material) forms a dominant phase around a filler material (Canadian Patent #2350112-2002). The filler is present in order to increase mechanical properties, and decrease material costs.

Conventional plastics are resistant to biodegradation, as the surfaces in contact with the soil in which they are disposed are characteristically smooth (Aminabhavi et al. 1990). Microorganisms within the soil are unable to consume a portion of the plastic, which would, in turn, cause a more rapid breakdown of the supporting matrix. This group of materials usually has an impenetrable petroleum based matrix, which is reinforced with carbon or glass fibers.

The second class of polymer materials under consideration is partially degradable. They are designed with the goal of more rapid degradation than that of conventional synthetic plastics. Production of this class of materials typically includes surrounding naturally produced fibers with a conventional (petroleum based) matrix. When disposed of, microorganisms are able to consume the natural macromolecules within the plastic matrix. This leaves a weakened material, with rough, open edges. Further degradation may then occur.

The final class of polymer materials is currently attracting a great deal of attention from researchers and industry. These plastics are designed to be completely biodegradable. The polymer matrix is derived from natural sources (such as starch or microbially grown polymers), and the fiber reinforcements are produced from common crops such as flax or hemp. Microorganisms are able to consume these materials in their entirety, eventually leaving carbon dioxide and water as by-products.

Materials must meet specific criteria set out by the ASTM and ISO in order to be classified as biodegradable. In general, the likelihood of microbial attack on a material is dependent on the structure of the polymer. When examining polymer materials from a scientific standpoint, there are certain ingredients that must be present in order for biodegradation to occur. Most importantly, the active microorganisms (fungi, bacteria, actinomycetes, etc.) must be present in the disposal site. The organism type determines the appropriate degradation temperature, which usually falls between 20 to 60°C (Shetty et al. 1990). The disposal site must be in the presence of oxygen, moisture, and mineral nutrients, while the site pH must be neutral or slightly acidic (5 to 8).

Biodegradation of materials occurs in various steps (Aminabhavi et al. 1990). Initially, the digestible macromolecules, which join to form a chain, experience a direct enzymatic scission. This is followed by metabolism of the split portions, leading to a progressive enzymatic dissimilation of the macromolecule from the chain ends. Oxidative cleavage of the

macromolecules may occur instead, leading to metabolization of the fragments. Either way, eventually the chain fragments become short enough to be converted by microorganisms (Stevens 2003).

Biodegradable polymers (those derived from plant sources) begin their lifecycle as renewable resources, usually in the form of starch or cellulose. As reported by Lorcks (1998), innovative polymer research and development leads to large scale production by plastic converters. The biopolymers are formed into the specific end products and used by a consumer. Ideally, the biopolymer will be disposed in a bio waste collection, and later composted. This process will ultimately leave behind carbon dioxide and water, which are environmentally friendly by-products.

BIOLOGICAL MATERIALS AND BIODEGRADABLE PLASTICS

Naturally occurring biopolymers are derived from four broad feedstock areas (Tharanathan 2003). Animal sources provide collagen and gelatine, while marine sources provide chitin which is processed into chitosan. However, the remaining two feedstock areas are the ones receiving the most attention from scientists, and are the sources thought to be the most promising for future development and expansion. Microbial biopolymer feedstocks are able to produce polylactic acid (PLA) and polyhydroxy alkanates (PHA). The final category of agricultural feedstocks are the biopolymer source under consideration at the University of Saskatchewan, in Saskatoon, Canada. This variety of polymers falls into the categories of hydrocolloids, and lipids and fats.

Starch is an agricultural feedstock hydrocolloid biopolymer found in a variety of plants including (but not limited to) wheat, corn, rice, beans, and potatoes (Salmoral et al. 2000, Martin et al. 2001). Starch is usually utilized in the form of granules, and is actually formed by one branched and one linear polymer (Chandra et al. 1998). Amylose, the linear polymer, comprises approximately 20% w/w of starch, while Amylopectin, the branched polymer, constitutes the remainder. Natural filler materials may be incorporated into synthetic plastic matrices as a rapidly biodegradable component. Often, granular starch is added to polyethylenes in order to increase the degradation rate of the plastic material.

Starch can also be used in its gelatinized form (Verhooght et al. 1995). Heating the starch in the presence of water during extrusion or injection moulding causes the formation of a thermoplastic material that may be deformed during blending. This starch-based product is then blended with either natural or synthetic materials. Heating starch above its glass transition temperature breaks its molecular structure, allowing further bonding (Jopski 1993). Glycerol is often used as a plasticizer in starch blends, to increase softness and pliability. Starch granules that have been plasticized with water and glycerol are referred to as plasticized starches (Martin et al. 2001). Plastic materials that are formed from starch-based blends may be injection molded, extruded, blown, or compression molded.

Agricultural feedstocks for the biopolymer industry also include fibres that are used as reinforcing fillers. This classification includes cellulose, which is the highly polar, main structural component of flax and hemp fibres (Bismarck 2002). Natural cellulose fibres are low cost, biodegradable, and have strong mechanical properties. These characteristics make cellulose fibres the most common choice for natural fillers in plastic materials. Hornsby et al. (1997) concluded that the presence of 25% w/w of cellulose fibres in a polypropylene matrix causes a significant increase in tensile modulus. Cellulose has a very long molecular chain, which is infusible and insoluble in all but the most aggressive solvents (Chandra et al. 1998). Therefore,

it is most often converted into derivatives to increase solubility, which further increases adhesion within the matrix.

Canadian researchers are particularly interested in expanding the area of fiber use in biopolymer products, as this would allow for value added processing of local agricultural waste products. Flax fibres continue to receive the majority of the consideration, as they are mechanically strong and readily available. Chemical treatment (acetylation) of the fibres is performed in order to modify the surface properties, without changing the fiber structure and morphology (Frisoni 2001). These modifications slow down the initiation of degradation of the fibres, and increase adhesion at the fiber and matrix interface. Bledzki et al. (1999) concluded that fibres that have been thoroughly dried prior to being added to the matrix show improved adhesion as opposed to fibres with a higher moisture content. Research has shown that polyvinyl alcohol is an appropriate polymer to use as a matrix in natural fiber reinforced composites, as it is highly polar and biodegradable (Chiellini et al. 2001).

Microbial biopolymer feedstocks produce biological polymers through microbial fermentation. The products are naturally degradable, environmentally friendly substitutes for synthetic plastics (Chau et al. 1999). A number of bacteria accumulate polyhydroxy alkanoates (PHAs) as intracellular carbon reserves when nutrient deficiencies occur. The biopolymers, which are microbially produced polyesters, have the same thermoplastic and water resistant qualities as synthetic plastics. It was concluded by Chau et al. (1999) that increasing the carbon to nitrogen (C:N) ratio in a chemical wastewater treatment system increased specific polymer yield (ie, the production of PHA's increased). Researchers have long been aware that practically any type of biomass can be converted into sugars through chemical or biological treatments. Certain organisms are then capable of forming PHAs from the sugars. Such is the case at the University of Hawaii, where food waste is being converted into PHAs (Petkewich 2003). Work in these areas continues, as the issue constricting expansion in the development of industry-wide PHA use is the high cost of producing the material. PHAs are brittle and expensive when used alone, so researchers opt to blend them with less expensive polymers, which have complementary characteristics.

Polylactic acid is the second common biopolymer which is produced by microbial fermentation. It is produced by the condensation of lactic acid, which is obtained through fermentation processes (Jopski, 1993). Wilkinson Manufacturing Co. (Fort Calhoun, Nebraska, USA) has recently introduced a commercially available thermoformed all-natural plastic container using a corn-based PLA. The carbon stored in the plant starches is broken down to natural plant sugars. Fermentation and separation form the PLA. PHA and PLA are both considered synthetic polymers, as they are not found in nature. However, they are wholly biodegradable (Stevens 2003).

There are a number of other biological materials that have been examined and manipulated by biopolymer researchers. Wheat contains starch and gluten, both of which are employed by the biopolymer industry. Canola derivatives have potential as both polymers and plasticizers (Crawford 2001). Chitosan is obtained from the deacetylation of chitin, which is found in marine environments. Because it is insoluble in water, chitosan is dissolved in acidic solutions before being incorporated into biodegradable polymer films (Park et al. 2001). The structural characteristics of soy proteins give them potential for industrial applications in plastics and reinforced composite materials (Park et al. 2000). As a general conclusion, it can be stated that many naturally occurring organisms (plant and animal) have potential to be modified and employed as biopolymers.

APPLICATIONS FOR BIODEGRADABLE POLYMERS

Research and development is only a portion of the work that is done in order to introduce the use of biodegradable polymer materials. The design of such materials usually begins with a conceptual application. It may be expected to replace an existing material, or to complement one. Sectors where applications for biopolymers have introduced include (but are not limited to) medicine, packaging, agriculture, and the automotive industry. Many materials that have been developed and commercialized are applied in more than one of these categories.

Biopolymers that may be employed in packaging continue to receive more attention than those designated for any other application. All levels of government, particularly in China (Chau et al. 1996) and Germany (Bastioli 1998), are endorsing the widespread application of biodegradable packaging materials in order to reduce the volume of inert materials currently being disposed of in landfills, occupying scarce available space. It is estimated that 41% of plastics are used in packaging, and that almost half of that volume is used to package food products.

BASF, a world leader in the chemical and plastic industry, is working on further development of biodegradable plastics based upon polyester and starch (Fomin et al. 2001). Ecoflex is a fully biodegradable plastic material that was introduced to consumers by BASF in 2001. The material is resistant to water and grease, making it appropriate for use as a hygienic disposable wrapping, fit to decompose in normal composting systems. Consequently, Ecoflex has found a number of applications as a packaging wrap.

Environmental Polymers (Woolston, Warrington, UK) has also developed a biodegradable plastic material. Known as Depart, the polyvinyl alcohol product is designed for extrusion, injection molding, and blow molding. Depart features user-controlled solubility in water, which is determined by the formulation employed. Dissolution occurs at a preset temperature, allowing the use of Depart in a variety of applications. Examples include hospital laundry bags which are "washed away" allowing sanitary laundering of soiled laundry, as well as applications as disposable food service items, agricultural products, and catheter bags (Blanco 2002).

The renewable and biodegradable characteristics of biopolymers are what render them appealing for innovative uses in packaging. The end use of such products varies widely. For example, biodegradable plastic films may be employed as garbage bags, disposable cutlery and plates, food packaging, and shipping materials. Guan and Hanna (2002) documented how biodegradable loose-fill packaging materials may be developed from renewable biopolymers such as starch. The starch material is treated by an acetylation process, chemical treatments, and post-extrusion steaming. Mechanical properties of the material are adequate, and true biodegradability is achieved.

The biopolymer materials suited for packaging are often used in agricultural products. Ecoflex, in particular, sees use in both areas. Young plants which are particularly susceptible to frost may be covered with a thin Ecoflex film. At the end of the growing season, the film can be worked back into the soil, where it will be broken down by the appropriate microorganisms. Li et al. (1999) concluded that the use of a clear plastic mulch cover immediately following seeding increases the yield of spring wheat if used for less than 40 days. Therefore, plastic films that begin to degrade in average soil conditions after approximately one month are ideal candidates as crop mulches.

Agricultural applications for biopolymers are not limited to film covers. Containers such as biodegradable plant pots and disposable composting containers and bags are areas of interest (Huang 1990). The pots are seeded directly into the soil, and breakdown as the plant begins to grow. Fertilizer and chemical storage bags which are biodegradable are also applications that material scientists have examined. From an agricultural standpoint, biopolymers which are

compostable are important, as they may supplement the current nutrient cycle in the soils where the remnants are added.

The medical world is constantly changing, and consequently the materials employed by it also see recurrent adjustments. The biopolymers used in medical applications must be compatible with the tissue they are found in, and may or may not be expected to break down after a given time period. Mukhopadhyay (2002) reported that researchers working in tissue engineering are attempting to develop organs from polymeric materials, which are fit for transplantation into humans. The plastics would require injections with growth factors in order to encourage cell and blood vessel growth in the new organ. Work completed in this area includes the development of biopolymers with adhesion sites that act as cell hosts in giving shapes that mimic different organs.

Not all biopolymer applications in the field of medicine are as involved as artificial organs. The umbrella classification of bioactive materials includes all biopolymers used for medical applications. One example is artificial bone material which adheres and integrates onto bone in the human body. The most commonly employed substance in this area is called Bioglass (Kokubo 2003). Another application for biopolymers is in controlled release delivery of medications. The bioactive material releases medication at a rate determined by its enzymatic degradation (Sakiyama-Elbert et al. 2001). PLA materials were developed for medical devices such as resorbable screws, sutures, and pins (Selin 2002). These materials reduce the risk of tissue reactions to the devices, shorten recovery times, and decrease the number of doctor visits needed by patients.

The automotive sector is responding to societal and governmental demands for environmental responsibility. Biobased cars are lighter, making them a more economical choice for consumers, as fuel costs are reduced. Natural fibres are substituted for glass fibres as reinforcement materials in plastic parts of automobiles and commercial vehicles (Lammers and Kromer 2002). An additional advantage of using biodegradable polymer materials is that waste products may be composted. Natural fibres (from flax or hemp) are usually applied in formed interior parts. The components do not need load bearing capacities, but dimensional stability is important. Research and development in this area continues to be enthusiastic, especially in European countries.

There are a number of novel applications for biopolymers, which do not fit into any of the previous categories. One such example is the use of biopolymer systems to modify food textures. For example, biopolymer starch (gelatin-based) fat replacers possess fat-like characteristics of smooth, short plastic textures that remain highly viscous after melting. Research continues into high pressure being used to manipulate biopolymers into food products. The eventual goal is improved physical characteristics such as foaming, gelling, and water- or fat-binding abilities (Ledward 1993). Biopolymer materials are currently incorporated into adhesives, paints, engine lubricants, and construction materials (Fomin et al. 2001). Biodegradable golf tees and fishing hooks (Canadian Patent # 2198680-1997) have also been invented. The attraction of biopolymers in all of these areas is their derivation from renewable sources, slowing the depletion of limited fossil fuel stores.

METHODS OF BIODEGRADATION

Just as important as the way in which a material is formed is the way in which it is degraded. A general statement regarding the breakdown of polymer materials is that it may occur by microbial action, photodegradation, or chemical degradation. All three methods are classified under biodegradation, as the end products are stable and found in nature.

Many biopolymers are designed to be discarded in landfills, composts, or soil. The materials will be broken down, provided that the required microorganisms are present. Normal soil bacteria and water are generally all that is required, adding to the appeal of microbially reduced plastics (Selin 2002). Polymers which are based on naturally grown materials (such as starch or flax fiber) are susceptible to degradation by microorganisms. The material may or may not decompose more rapidly under aerobic conditions, depending on the formulation used, and the microorganisms required.

In the case of materials where starch is used as an additive to a conventional plastic matrix, the polymer in contact with the soil and/or water is attacked by the microbes. The microbes digest the starch, leaving behind a porous, spongelike structure with a high interfacial area, and low structural strength. When the starch component has been depleted, the polymer matrix begins to be degraded by an enzymatic attack. Each reaction results in the scission of a molecule, slowly reducing the weight of the matrix until the entire material has been digested (Shetty et al. 1990).

Another approach to microbial degradation of biopolymers involves growing microorganisms for the specific purpose of digesting polymer materials. This is a more intensive process that ultimately costs more, and circumvents the use of renewable resources as biopolymer feedstocks. The microorganisms under consideration are designed to target and breakdown petroleum based plastics (Andreopoulos et al. 1994). Although this method reduces the volume of waste, it does not aid in the preservation of non-renewable resources.

Photodegradable polymers undergo degradation from the action of sunlight (ASTM 883-96). In many cases, polymers are attacked photochemically, and broken down to small pieces. Further microbial degradation must then occur for true biodegradation to be achieved. Polyolefins (a type of petroleum-based conventional plastic) are the polymers found to be most susceptible to photodegradation. Proposed approaches for further developing photodegradable biopolymers includes incorporating additives that accelerate photochemical reactions (e.g. benzophenone), modifying the composition of the polymers to include more UV absorbing groups (e.g. carbonyl), and synthesizing new polymers with light sensitive groups (Andreopoulos et al. 1994). An application for biopolymers which experience both microbial and photodegradation is in the use of disposable mulches and crop frost covers.

Some biodegradable polymer materials experience a rapid dissolution when exposed to particular (chemically based) aqueous solutions. As mentioned earlier, Environmental Polymer's product Depart is soluble in hot water. Once the polymer dissolves, the remaining solution consists of polyvinyl alcohol and glycerol. Similar to many photodegradable plastics, full biodegradation of the aqueous solution occurs later, through microbial digestion. The appropriate microorganisms are conveniently found in wastewater treatment plants (Blanco 2002). Procter & Gamble has developed a product similar to Depart, named Nodax PBHB. Nodax is alkaline digestible, meaning that exposure to a solution with a high pH causes a rapid structural breakdown of the material (Leaversuch 2002). Biopolymer materials which disintegrate upon exposure to aqueous solutions are desirable for the disposal and transport of biohazards and medical wastes. Industrial "washing machines" are designed to dissolve and wash away the aqueous solutions for further microbial digestion.

ENVIRONMENTAL IMPACTS OF BIOPOLYMERS

Engineers are attempting to integrate environmental considerations directly into material selection processes, in order to respond to an increased awareness of the need to protect the environment (Thurston et al. 1994). The use of renewable resources in the production of

polymer materials achieves this in two ways. First of all, the feedstocks being employed can be replaced, either through natural cycles or through intentional intervention by humans. The second environmental advantage of using renewable feedstocks for biopolymer development is the biodegradable nature of the end products, thereby preventing potential pollution from the disposal of the equivalent volume of conventional plastics. At the end of their useful period, biopolymer materials are generally sent to landfills or composted.

Recycling of plastic materials is encouraged and well advertised, but attempts at expanding this effort have been less than effective. In the United States, currently less than 10% of plastic products are recycled at the end of their useful life (Chiellini et al. 2001). Recycling must be recognized as a disposal technique, not a final goal for material development. A complacent attitude regarding recycling processes ignores the fact that advanced infrastructure is needed to properly house recycling. As Mulder (1998) discovered, in underdeveloped countries plastics are almost completely recycled, as the return on investment is positive in their economic situation. This appears to be positive at the onset, but the open systems by which the plastics are recycled allow the emission of toxic gases at crucial levels.

Recycling appeared to be a viable way to reduce pollution and environmental damage when it was first introduced as a waste reduction technique. However, as time has passed, it is now obvious that the use of plastics based on renewable feedstocks which are biodegraded is a more sensible choice than recycling conventional plastics, as the end products are organic matter, and toxic emissions are avoided. Therefore, growth of plastics which are compostable or easily degraded must be encouraged.

In recent years, concern about a perceived garbage crisis has grown. Landfills have reached capacity, and sites for new landfills are difficult to find. When biopolymers are disposed in landfill environments, the hope is that the necessary microorganisms will be present. Unless the soil is inoculated with them, this may not always be the case. As reported by Petkewich (2003), carrots have been found to remain orange, and grass clippings green, after years in a landfill. Inoculation with bacteria, fungi, and actinomycetes is effective in encouraging biopolymer breakdown within soil (Orhan et al. 2000). However, if the appropriate microorganisms are present, the disposal (and consequential breakdown) of biodegradable (or partially biodegradable) plastic materials will lead to an increase of available space in current landfills as the volume of waste is reduced through biodegradation (Simon et al. 1998).

Compostable plastics undergo biological degradation during composting to yield carbon dioxide, water, inorganic compounds, and biomass at a rate consistent with other known compostable materials, and leave no visually distinguishable or toxic residues (ASTM 1996). Many of the biodegradable plastic materials discussed thus far were designed to be compostable. For instance, the purpose of designing disposable plastic cutlery and plates is that they can be thrown into a compost heap with leftover food. The requirements of biopolymers to be included in industrial composters are complete biodegradation and disintegration, and that there be no effect on compost quality as a result of biopolymer degradation (Wilde and Boelens 1998).

As an added benefit, Nakasaki et al. (2000) concluded that odor emissions from compost piles are reduced when biodegradable plastic is included in the mix. Ammonia, a noxious gas, is produced by the decomposition of compost. The degradation of biodegradable plastics produces acidic intermediates, which neutralize the ammonia content, thus reducing odor problems.

The 1970's began an era of increased factual thinking processes by researchers and industry officials. As such, the technique of life cycle analysis (LCA) emerged. This modeling exercise is based on a simple idea; it is necessary to look at the complete life cycle for the production, use, and disposal of a product in order to obtain a clear picture of the true environmental

implications of its development (Boustead 1998). Performing an LCA demonstrates whether or not further development of a product is a viable option. There are three steps to an LCA, beginning with the inventory, where inputs and outputs of the system are quantitatively described. The interpretation step follows, which links the inputs and outputs with observable environmental effects. Finally, the improvement step is carried out. Here, the system is redesigned to remain functional, while showing increased environmental awareness. The cycle is repeated until an objective decision can be made as to the environmental efficiency of the system.

The technique of life cycle analysis is a good way to examine the practicality of further development of biopolymer materials. Only by exploring all implications of the product can its true environmental responsiveness be judged. As society continues to become more aware of environmental issues, the procedure of LCA will continue to be used more often. On the other hand, further acceptance of integrated waste management techniques for biodegradable plastic materials, involving efficient material use and disposal must also continue (Subramanian 2000).

ECONOMIC IMPACTS OF BIOPOLYMERS

From the viewpoint of industry, the greatest advantage of using biopolymers derived from renewable feedstocks is their low cost. At a first glance, biopolymers appear to be a win-win opportunity for the economy and the environment. However, as is the situation with environmental issues, a closer look at the cost-performance ratio of biopolymers must be taken in order to make sound economic decisions (Swift 1998).

According to Leaversuch (2002), cost is a stumbling block for synthetically derived biodegradable plastic materials when they are directly compared with their conventional counterparts. As the case with any new material, manufacturers must expect a minimum of two years of losses before a profit is returned. Leaversuch also indicated that a key factor restricting growth of biopolymer industries is that the infrastructure for sorting and composting organic waste is developing more slowly than was initially expected.

Many reports paint a more optimistic picture for the economic promise of biopolymers. As Salmoral et al. (2000) reported, a number of major chemical companies are gaining interest in developing biopolymer technologies used to manufacture products from renewable resources. Tharanathan (2003) reported that synthetic plastics will never be totally replaced by biodegradable materials. However, he believes that in niche markets where the development is feasible, there exists an opportunity for manufacturers to find a large profit.

One sector in which economic benefits exist from the use of biopolymer materials is in the automotive industry. With respect to fiber reinforcements, widely employed traditional glass fibres are abrasive, and quickly wear down processing equipment. The texture of flax fibres is less coarse, prolonging the life of processing equipment (Stamboulis et al. 2000). Williams and Pool (2000) identified that natural fibres are advantageous over synthetic ones because they are less expensive and more readily available. The expansion of flax fiber incorporation into automobile parts is a positive development for Canada's agriculture industry, particularly in its diversification efforts.

Another application of natural fiber reinforcement has been developed in the use of China reed fiber to reinforce transport pallets. This was an economically sound decision, as the China reed pallets are as mechanically stable as conventional pallets, but they are less expensive to create, and need a shorter lifespan for cost recovery. Logistically, the China reed pallets are also more economic than the conventional type because their lighter mass requires less fuel for transport (Corbiere-Nicollier et al. 2001).

Work continues in the development of the biopolymer industry to a point where it is completely economically competitive with the conventional plastic industry. Synthetic plastics are produced on a large scale, while for the most part biopolymers are currently produced on a small scale. The inexpensive nature of the renewable resource feedstocks is encouraging researchers and industry officials to invest time to further develop these processes.

As the production of biopolymers expands, so too will the services associated with it. For example, facilities where flax straw is decorticated and processed into fibers are necessary for further expansion of flax fiber incorporation as material reinforcements (Lammers and Kromer 2002). In the case of microbially-grown polymers, large fermentation and separation facilities are needed for the further use of such materials. As a general summary, it may be stated that time will lead to greater economic strength for the incorporation of biopolymer materials into society.

THE FUTURE OUTLOOK FOR BIODEGRADABLE PLASTICS

There is room for growth and expansion in many areas of the biodegradable plastic industry. Chau et al. (1999) estimates that plastic waste generation will grow by 15% per year for the next decade. Carbon dioxide emissions from the formation and disposal of conventional plastics are reaching epic levels. The complete substitution of petroleum-based feedstock plastics by renewable resource-based feedstock ones would lead to a balanced carbon dioxide level in the atmosphere (Dahlke et al. 1998). However, it is ludicrous to expect a full replacement of conventional polymers by their biodegradable counterparts any time soon. Expansion into particular niche markets seems to be the most viable option.

Researchers worldwide are interested in the area of biopolymer development. The German government has stringent regulations in place regarding acceptable emission levels. In 1990, the German government published a call for research and development of biodegradable thermoplastics (Grigat et al. 1998). For this reason, many German material scientists and engineers have focused their work on environmentally stable biodegradable plastics. Various materials have been created by these researchers, including the Bayer BAK line which was introduced in extrusion and injection moulding grades in 1996. Novamont, an Italian company, introduced the Mater-Bi line for similar reasons. Queen Mary University in London, England has a plastics department which is actively working on biocomposite development (Hogg 2001). As a whole, all European nations are expected to follow the European Packaging directive, which expects a material recovery of packaging waste. Organic recovery (composting spent materials) is the most commonly applied waste reduction method (Schroeter 1998). European nations are also expected to incorporate 15% w/w of recycled plastics into the manufacture of packaging materials. Germany aims to better that level, as they set tier goal in 2001 for a 60% incorporation of recycled plastics into new packaging materials (Fomin et al. 2001).

European nations are the front runners of biopolymer research, but impressive developmental work has occurred, and continues to occur, in other geographical areas. The Chinese government is responsible for a large population on a small land base. Therefore, the preservation of space, and responsible disposal of waste are key considerations. For these reasons, Chinese researchers are focussing on refinement of microbially produced PHA (Chau et al. 1996). North American researchers, including those at the University of Saskatchewan, are also interested in biopolymer development, as the agricultural industry will benefit from the potential value added processing. The acceptance of the Kyoto Accord by the Government of Canada is fueling a need for the reduction of use of fossil fuel feedstocks, and an increase in the use of renewable resource feedstocks. Biodegradable plastics fulfill this requirement.

As the biopolymer industry grows, issues with production will be worked out. There are some areas of concern that researchers are aware of, and are consequently focussing on. Multilayer films containing starch and/or natural fibres tend to have adhesion problems (Frisoni et al. 2001, Martin et al. 2001). The search for an ideal processing technique to circumvent this problem continues. In this regard, Verhoogt and co-workers (1995) have concluded that additional starch content in thermoplastic blends increases flexibility, but decreases mechanical strength. As reported by Van Soest and Kortleve (1999), direct relations between processing, structure, and properties of starch based materials are inconclusive.

Standards organizations such as the ASTM and ISO have published methods for material tests on biodegradable plastic materials. A need for reviews and improvements of these tests has come to light as industry expands its use of biopolymers. In particular, non-homogenities are created in polymer materials by the clamps used for tensile tests (Nechwatal et al. 2003). The nature of natural materials requires different considerations than those for synthetic materials.

The biopolymer industry has a positive future, driven mainly by the environmental benefits of using renewable resource feedstock sources. The ultimate goal for those working in development is to find a material with optimum technical performance, and full biodegradability.

CONCLUSIONS

There are a seemingly limitless number of areas where biodegradable polymer materials may find use. The sectors of agriculture, automotives, medicine, and packaging all require environmentally friendly polymers. Because the level of biodegradation may be tailored to specific needs, each industry is able to create its own ideal material. The various modes of biodegradation are also a key advantage of such materials, because disposal methods may be tailored to industry specifications.

Environmental responsibility is constantly increasing in importance to both consumers and industry. For those who produce biodegradable plastic materials, this is a key advantage. Biopolymers limit carbon dioxide emissions during creation, and degrade to organic matter after disposal. Although synthetic plastics are a more economically feasible choice than biodegradable ones, an increased availability of biodegradable plastics will allow many consumers to choose them on the basis of their environmentally responsible disposal.

The processes which hold the most promise for further development of biopolymer materials are those which employ renewable resource feedstocks. Biodegradable plastics containing starch and/or cellulose fibres appear to be the most likely to experience continual growth in usage. Microbially grown plastics are scientifically sound, and a novel idea, but the infrastructure needed to commercially expand their use is still costly, and inconvenient to develop.

Time is of the essence for biodegradable polymer development, as society's current views on environmental responsibility make this an ideal time for further growth of biopolymers.

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