GREEN PLASTICS: AN EMERGING ALTERNATIVE FOR PETROLEUM-BASED PLASTICS?

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Abstract

Plastics are referred to as "green" if they exhibit one or more of the following properties: source renewability, biodegradability/compostability at end of life, and/or environmentally friendly processing. World plastics production and consumption is increasing every year and so is a growing concern about its impact on the environment. The vast majority of plastics today originate from petroleum-based hydrocarbons and therefore are made from non-renewable resources. Even though less than 5% of all petroleum is used in plastics manufacturing, the renewability of the source is often a concern. Separation of different types of petroleum-based recyclable plastics from other solid wastes is a difficult and labor-intensive process; hence only a very small percentage of plastics are recycled. The inability of petroleum-based plastics to biodegrade is also criticized by environmentalists. As a response to these issues, there has been an increasing interest in what are called "green plastics."

Green plastics are being widely publicized as a possible solution for concerns regarding the use of traditional petroleum-based plastics. Materials such as polylactic acid (PLA) are examples of renewable plastics used for plastic products that are traditionally made using petroleum-based plastics such as polyethylene terephthalate (PETE), polystyrene (PS), and polypropylene (PP). Several challenges could be faced in an attempt to replace petroleum-based plastics with green plastics. Physical properties, chemical resistance, processing, and recycling are just a few potentially problematic areas. This paper is an investigation into facts about green plastics, their current status, advantages, shortcomings, and other related issues. The conclusion reached would comment on the future of green plastics and whether they can replace petroleum-based plastics.

Introduction

"Green," "sustainable," and "renewable" are some of the most frequently heard buzzwords nowadays. In the United States and the rest of the world, advertisements and campaigns from different businesses, organizations, and governmental agencies meant to educate people about advantages of going green have become commonplace. The corporate world is trying to show its commitment to and investment in sustainability. As most people may agree, one of the most common targeted materials when it comes to sustainability is plastics. The impact of the plastic industry on the US economy is significant. According to the Society of the Plastics Industry (www.plasticsindustry.org), the trade association based in Washington, D.C., plastics is the nation's third largest manufacturing industry. Since 1980, the plastics industry has grown at a rate averaging 3.4 percent. US plastics companies employ 1.1 million workers and provide nearly $379 billion in annual shipments [1].

Along with growing plastics production and consumption is a growing concern about impact on the environment. The source for most commercial plastics is petroleum, which is considered a non-renewable resource. Even though less than 5% of all petroleum is used in plastics manufacturing, the renewability of the source is a concern, as it takes millions of years for fossil fuels to be replenished. In addition, most commodity plastics (bottles, cups, etc.) made out of petroleum are non-compostable and non-biodegradable. Separation of different types of petroleum-based recyclable plastics from other solid wastes is a difficult and labor-intensive process; hence only a very small percentage of such plastics are recycled, leaving the rest in landfills. Most of the commodity plastic materials are used for food packaging and therefore are either contaminated or difficult to clean for recycling. In addition, it costs more to recycle common commodity plastics such as polyethylene terephtalate (PET) than to produce new plastics from scratch [2]. As per Environmental Protection Agency (EPA) statistics, plastics waste is one of the fastest-growing sectors in the Municipal Solid Waste (MSW) segment, and the majority of plastic wastes originate from packaging materials [3]. The amount of solid plastics waste generated in 2007 was estimated to be approximately 30.7 million tons, which accounts for almost 12.7% of the total MSW. The amount of plastic waste after recovery was almost 28.6 million tons, meaning that just less than 7% was recovered while aluminum and paper were recovered at rates of 33.8% and 54.5% respectively [3]. Plastics manufacturers have been trying to reduce the flow of solid waste with source reduction, recycling at source, etc. All such methods have their own limitations and can only address the solid waste generation to an extent.

History

Green plastics made from naturally occurring renewable resources are being widely publicized as a possible solution for concerns regarding the use of traditional petroleum-based plastics. Bioplastics materials such as polylactic acid (PLA) are often projected as replacement for traditionally-made petroleum-based plastics such as polyethylene terephthalate (PETE), polystyrene (PS), and polypropylene (PP) in commodities manufacturing. The history of plastics made from non-petroleum resources goes back to 1868 when John W. Hyatt invented celluloid [1]. Celluloid was made from wood pulp, plant fibers (cellulose), or cotton fibers treated with nitrogen and camphor. Soon cellophane and rayon were invented by treating cellulose with other acids and solvents. In 1907 with the invention of the first petroleum-based plastics, Phenol Formaldehyde (Bakelite) by Leo Bakeland, the history of bio-based plastics took a twist. Since then, bioplastics became sidetracked in favor of petroleum-based plastics. In the 1920s, in an effort to find applications for agricultural surplus, Henry Ford experimented with manufacturing automobile parts from plastics made out of soya beans [4]. The resin for soy plastics was not completely plant-based; part of it was composed of phenol formaldehyde. Ford's soy plastic idea did not survive for a variety of reasons, including lack of molding technology for manufacturability of complex parts and noticeable formaldehyde odor from the parts [4]. After the industrial revolution following World War II, the only non-petroleum-based plastic that was steadily growing in consumption was cellophane.

Definition of Green Plastics

The definition of green plastics has changed from the days of Ford's soy-based plastics. Plastics are referred to as "green" if they exhibit one or more of the following properties: source renewability; biodegradability/compostability after life; and/or environmentally friendly processing, lifecycle, and afterlife disposal [4]. The term "bioplastics" is often used in books and articles referring to green plastics, and the terminology could be confusing. Bioplastics could be biodegradable plastics (those which degrade) or bio-based plastics (synthesized from renewable biomass) [5]. Not all biodegradable plastics are bioplastics (some oil-based plastics are biodegradable), and not all bio-based plastics are biodegradable. Biodegradability of a material mostly depends on its chemical structure [6]. Plastics being polymers, most oil-based plastics have a strong carbon-carbon single bond which is difficult to break, hence making it non- degradable. For example, polyethylene (developed by Braskem, a Brazilian petrochemical company) made from renewable masses such as sugarcane is not biodegradable but is recyclable [7]. Green plastics are also referred to as biopolymers. These natural polymers are inherently biodegradable because of the oxygen or nitrogen atom in their polymer backbones, as opposed to the carbon-carbon single bond in petroleum-based polymers. According to the American Society for Testing and Materials (ASTM), in order for a biodegradable plastic to be classified as compostable, it should yield carbon dioxide, water, and inorganic compounds at a rate consistent with other known compostable materials. In essence, a biodegradable plastic degrades from the action of naturally occurring microorganisms such as bacteria, whereas a compostable plastic undergoes biological processes to yield carbon dioxide, water, and other inorganic compounds which are non-toxic [8].

Previously, renewability of materials mostly pointed toward the renewability of the source, whereas now it is redefined in terms of the carbon footprint the material leaves. For example, when comparing corn to sugarcane, both being sources for ethanol, corn uses more fertilizer than sugarcane. The manufacture of fertilizers consumes natural gas, thereby causing corn to have a large carbon footprint [9]. "Environmentally friendly nature" refers to the direct and indirect impact the plastic has on the environment. This could be direct impacts during processing such as the usage of water or the amount of solid waste generated after life, or indirect impacts such as the amount of electricity consumed, the additional cost in transportation because of higher specific weight, etc.

Several challenges could be faced in an attempt to replace petroleum-based plastic products with green plastics. Physical properties, chemical resistance, processing, recycling, and cost are just a few potentially problematic areas. These limitations have set the application of bioplastics to certain niche markets accounting for 0.3% of global plastic production (according to 2007 estimates) [2]. But organizations such as the industry association European Bioplastics foresee a 37% annual growth rate in the bioplastics market by 2013 [2]. Still, critics are skeptical about the ability of green plastics to serve as an alternative for petrochemical-based polymers. This paper is a review of the current status of green plastics, major developments in the area, and challenges faced. The conclusions reached would comment on the future of green plastics and whether they can replace petroleum-based plastics.

Green Plastics Classification

E. S. Stevens classifies modernday green plastics into three categories [4]:

(i) Polymers extracted directly from biomasses (plants or animals), with or without modification. (Referred to as Type I hereafter.) For example, polysaccharide starch modified polymers and polymers derived from cellulose.

(ii) Polymers processed directly by microorganisms through large-scale fermentation processes. (Referred to as Type II hereafter.) For example, polyhydroxyalcanoates (PHA), copolymers of Polyhyrodxybutyrate and hydroxyvalerate (PHBV).

(iii) Polymers obtained from resins (monomers) produced with renewable and naturally occurring raw materials. (Referred to as Type III hereafter.) For example, polyesters such as polylactic acid (PLA) processed from naturally occurring lactic acid monomers.

Table 1 is a snapshot and description of all three types of plastics mentioned above, and their advantages and disadvantages. Of the three categories in Table 1, the polymers that are produced from naturally occurring monomers are widely gaining popularity because of their physical, chemical, and biological properties as well as their cost effectiveness in mass production. Polylactic acid (PLA), co-developed by Nature Works LLC, a subsidiary of Cargill, is one of such polymers finding increased attention. PLA is finding widespread applications for a short product life, with low-performance disposable packaging production. PLA usage has been significantly growing since 1998 [10]. Estimated production of PLA by 2013 is approximately 450 thousand tons per year. Some 70% to 80% of PLA is utilized for packaging purposes such as cups, trays, etc. [11]

Table 1. Green Plastics Materials and Properties

Type	Origin	Examples	Products	Utility	Disadvantages	Advantages
I	Extracted directly from biomass	Polysacchacharides (Starch)	Non-Durable Goods: packaging	Medium	Modest strength, poor water resis-sis-tance	Low cost
II	Polymer from large scale fermentation of biomass	PHBV	Durable Goods: toiletry and office accessories	Low	Synthesizing cost, Narrow melting range	Superior physical properties, good water resistance
III	Monomer extracted from biomass	PLA	Non Durable goods: Disposable plates, cups, boxes, film wraps	High	Low thermal resis-sis-tance, brittle-tle-ness, high specific weight	More cost effective than Type II, optical clarity, good moisture resistance

Processing Green Plastics

Products made of biodegradable plastics must be stable during processing. Most green plastic materials are processed by methods such as thermoforming, injection molding, blow molding, and extrusion [12]. These processes demand certain mechanical and physical properties such as melt strength, flow, elongation, temperature resistance, and elasticity. Most green plastic materials have modest strength, low water and temperature resistances, lower impact strength, etc. Therefore these materials require improvement and modification, and hence most commercial bioplastics are composed of several chemicals such as additive stabilizers, colorants, etc. which makes it almost impossible for them to be manufactured from 100% renewable resources (most bioplastics now contain 50% renewable resources) [13]. These additives must meet standards for compostable plastics such as ASTM D6400. Therefore, the bioplastics industry sees a shift in the marketplace from compostability to renewability partly due to lack of facility infrastructure here in the United States [14].

Higher specific weight of commonly used bioplastics materials such as PLA is always an issue. PLA, often used in packaging, has a high specific weight (1.24g/cc) compared to PP (.90g/cc) and PS (1.04g/cc), which implies more material usage and processing cost for a given packaging. PLA also has less resistance to prolonged temperature exposure over 130°F [15]. The low impact resistance of PLA and its low melting point is another downside of it being used in packaging applications. Athena Institute International, a nonprofit research and development firm, compared sixteen-ounce drink cups, deli containers, envelop window film, foam trays, and twelve-ounce containers made using PLA with ones made using equivalent PET and PP [16]. The study observed total energy consumed, solid waste generated, and greenhouse gases emitted during the manufacture of the abovementioned products. From fabrication to grave, most of the PLA packaging generated more solid waste and consumed more energy for production. The greater energy consumption was due to the fact that PLA underwent extra processing steps (more cooling time) as well as required more material to make a given size product. The study found that PLA is difficult to degrade in household compost pits and would emit an amount of greenhouse gases comparable to that of traditional oil-based plastics. The study also noted that possible mixing of PLA with PET in the existing recycling system could end up harming the reusable PET. At the same time, advocates argue that the additional crops cultivated to produce green plastics would remove a substantial amount of carbon dioxide from the atmosphere.

Most biopolymers seem to be tough to process because there is a small window between processing temperature and decomposition point. Injection molding has large application in bioplastics products starting from durable goods such as toys, tools, bathroom accessories, etc. to non-durable goods such as packaging. The biggest challenges in injection-molding bioplastics are heat, moisture, and degradation caused by excessive temperature, shear or residence time [17]. Modifications need to be made to barrel temperature profile, mold temperature, screw speed, screw back pressure, and injection speed [18]. Materials such as PLA tend to hold heat for a longer time, and therefore would require higher cooling time. PLA also tends not to flow well over long distances. Materials such as PHA tend to respond better to slower injection speed which means higher cycle time. Increasing pressure would increase shear which can cause it to break down [17]. Unmodified biopolymers resins are hygroscopic and if not dried properly (as low as 250ppm) can result in decreased molecular weight and dropped melt viscosity, generating more flash and trim wastes. Even though most of the bioplastics resin manufacturers endorse using traditional thermoplastic machinery, they recommend avoiding high-shear screws and hotspots in the barrel. Also most of the bioresins cannot be left at the machine at the end of the work day to prevent excessive degradation. Extruding bioplastics with general purpose polyolefin screw may be less efficient due to lack of drive because of the inferior flow property [11]. The higher specific weight necessitates sturdier roll handling equipments and reinforced hoppers. Also, the cooling rolls after extrusion need to remove more heat compared to materials such as PS [11]. One of the major difficulties in thermoforming PLA is its narrow softening range which makes the process very hard to control. PLA's higher tensile strength and lower elongation properties could make thermoforming difficult [19]. Other obstacles while thermoforming PLA include its low melt strength which could cause shearing when stretched.

Recycling Issues

Plastics recycling falls into two categories: pre-consumer and post-consumer [20]. Pre-consumer recycling involves waste generated during manufacture of the product, such as trim wastes after thermoforming or runner and sprue waste from post-injection molding. Most manufacturers are focused on recycling the pre-consumer waste at the source itself. The problem arises with post-consumer recycling of bioplastics after its end use. Recycling post-consumer waste is a tedious and expensive process as it involves a considerable amount of cleaning and sorting. With petroleum-based plastics, it is not easy to determine the differences between similar plastics such as PE or PP. One of the major hurdles in recycling is that these different polymers are not mixable. Mixing of bioplastics with petroleum-based plastics could contaminate the oil-based plastic feed generated from recycling. A mixture could result in inferior properties leading to a recycled plastic that is unusable for many processes. This is very likely to happen as consumers may not differentiate between different plastic types. Therefore, bioplastics should be from identifiable sources that will allow for sorting. In the United States, little infrastructure currently exists to collect bioplastics in sufficient quantities, and consumers do not have a clear picture on its recyclability. Another way to deal with post-consumer plastics is composting. It should be noted that one of the biggest myths about landfills is that they are giant compost pits, which is not true. In fact, anything that goes into a landfill (bioplastics or oil-based plastics) that lacks exposure to sunlight and air will not decompose properly. Therefore, bioplastics composting needs additional infrastructure and settings to handle the volume. Commercial bioplastics such as PLA can compost only in municipal and industrial compost settings [21]. Therefore, the composting sector has to expand to accommodate the growing waste generated from bioplastics.

Synthetic Blending

A large amount of green plastics' shortcomings are overcome by synthetic blending. For example, Novamont, Europe's largest bioplastics producer, produces Mater-Bi which is a blended bioplastic composed of starch and other fully biodegradable synthetic polymers[22]. Blending can overcome property shortcomings such as water resistance, strength, and elasticity. BASF's Ecovio, which is fully biodegradable, is another example of synthetic blending where 45%Naturework's PLA (made from lactic acid) is combined with 55%Ecoflex (made from petrochemicals). Combining Ecoflex, which is softer with higher elongation properties, and PLA, which is rigid with higher tensile strength, resulted in Eco-Vio, which falls in between two points, making it a suitable material for packaging and other non-durable goods. Starch-based biopolymers have poor water resistance and modest strength. In order to overcome these shortcomings, it is mixed with polyethylene or totally biodegradable polyvinyl alcohol [4]. Sometimes starch-based polymers are coated with PHBV to obtain better water resistance. Teknor Apex Co, another blender, is targeting on producing alloys of thermoplastic starch with materials such as PLA, PHA, and PP. Professor Richard Larock at Iowa State University has been successful in simply combining natural oils (up to 85%) with conventional plastic monomers to produce a synthetic blend which is claimed to have better thermal properties and shape memory properties [2]. A question arises whether some of the synthetic materials may have a non-renewable source, resulting in less than 100%-green plastics.

Standards and Certifications

In the United States, ASTM D-6400 specifications for compostable plastics covers plastics and products made from plastics that are designed to be composted in municipal and industrial aerobic composting facilities [23]. The ASTM D-6868 specification covers biodegradable plastics and products (including packaging), where plastic film or sheeting is attached (either through lamination or extrusion directly onto the paper) to substrates and the entire product or package is designed to be composted in municipal and industrial aerobic composting facilities [22]. Similar standards exist elsewhere, such as the German (DIN-54900), European (EN-13432), and international (ISO-14855) standards. Professional associations such as the Biodegradable Products Institute (BPI), which comprises key individuals and groups from government, industry, and academia, promotes the use and recycling of biodegradable polymeric materials (via composting). They have an established series of specifications, and standards for compostability (based on ASTM D6400 and D6868), which if met will allow the product to display the BPI logo. Similarly, in Japan, Japan Bioplastics Association (JBPA) has started the BiomassPla certification to distinguish products made from biomasses [24]. Certification in other countries includes EcoLogo (Canada) and Vincotte (Belgium). These endorsements and certifications could boost consumer confidence regarding biodegradability of a given product. Consumer certainty is critical to the growth of the bioplastics industry, as studies in Europe and Japan have shown that consumers are willing to spend the extra dollar for sustainable products [25].

Cost Factor

Cost is a significant factor when it comes to most plastics applications, especially disposable ones such as packaging. For example, if a small bag of chips from a vending machine costs $1.00, then the cost of the bag should not be a significant portion of it. The cost per pound for bioplastics has dropped significantly in recent years. For example, PLA, which cost $3/lb in the 1990s has dropped to 90 cents/lb in 2010. The rise in the price of oil has made bio-based plastics prices comparable to the price of oil-based commodity thermoplastics. Still, additional cost incurred due to increased processing steps, high specific weight, and several other factors could be impediments to bioplastics usage. Along with growing concerns regarding utilizing agricultural land for production of raw bio materials such as corn, one of the other obstacles for growth of bioplastics is the increasing price due to competition from the food industry [10]. However, some critics argue that this is not the case. According to Blackburn, the land mass necessary to produce 500,000 tons of PLA is less than 0.5% of the annual US crop [26]. Currently, with bioplastics being only less than 1% of the total plastics used, the concern regarding agricultural land usage may not be an issue. But according to Evans, if bioplastics usage grows to 10%, 5 billion pounds of starch will be required, which could make an impact on agriculture. Also, the increased use of crops such as corn in the production of ethanol has caused prices to double in the past year [2].

Conclusions

Current market trends regarding the growth of bioplastics look promising. Significant growth has been observed in patents deposits for bioplastics such as PLA, which had 20 patents deposited in 1998 versus 330 in 2005[10]. Bioplastics demand is expected to hit an annual production level of 2% of global thermoplastics production, which is approximated at 250 million tons annually. Major manufacturers and even governments are focusing on renewability of plastics. For example, the Japanese government has set a target for the year 2020 to produce 20% of their plastic from renewable sources. Toyota targets making 20% of their interior trims from renewable sources by 2020. Ford is currently using soy-based polyurethane on the seats of twenty-three of its models. Consumer products giant P&G has a long-term goal set to make all of its packaging renewable or recyclable, and replacing 25% of its packaging materials with “sustainably sourced material” [27]. Wal-Mart, the world’s biggest retailer, is demanding packaging made from renewable resources [28]. All these steps could be real indications of an existing commitment and an upcoming demand.

The green plastics industry is still in its infancy and may not be ready to replace the petrochemical-based plastics. At the same time, this sector is preparing for growth and getting ready to meet increased demand. Still, there are challenges in processing, material properties, and recycling to be faced when attempting to replace the petrochemical-based plastics. Most bioplastics are currently utilized for non-durable goods such as packaging. Plastics such as PHA have properties comparable to their petroleum-based counterparts and could be used for durable goods. The fermentation step in processing makes the raw material expensive. Research is underway in processing such polymers without fermentation [22]. Green plastics with a wide range of properties that could allow them to be processed like conventional plastics need to be developed. One real problem that exists is in defining and identifying green plastics. There needs to be a better understanding of what constitutes “greenness.” A venture between governments, industry, and society (such as BPI) could play an extensive role in educating society on what “greenness” truly means. Standardizations and certifications of sustainability should be publicized extensively. A globally accepted system of standards for green plastics could help manufacturers and producers focus their efforts toward a common goal. Infrastructure for collection and composting of degradable plastics needs to be improved. Governmental incentives such as tax cuts and rebates could also help promote greenness. Diversification of feed stocks from food crops to alternative biomass materials could have a positive impact on the cost as well as alleviate concerns regarding use of agricultural land. There seems to be a lot of enthusiasm in society, industry, and government regarding greenness. If the trend continues, and the motivation for innovation in this field persists, the results could be promising.

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Biography

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