Green Plastics: An Emerging Alternative for Petroleum Based Plastics?

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Abstract

Plastics are referred "green" if they exhibit one or more of the following properties: source renewability, biodegradability/compostability after end of the life and environmentally friendly processing. World plastics production and consumption is increasing every year and so is a growing concern about its impact on the environment. Vast majority of the plastics today are originated from petroleum based hydrocarbons and therefore made from non renewable resources. Even though less than 5% of the 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 intense 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 increasing interest in what is 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 poly lactic acid (PLA) are examples of renewable plastics used for plastic products which are traditionally made using petroleum based plastics such as polyethylene terephthalate (PETE), polystyrene (PS), polypropylene (PP). Several challenges could be faced in an attempt to replace petroleum based plastics product with green plastics. Physical properties, chemical resistance, processing, recycling etc. are to name a few. This paper is an investigation into facts about green plastics, its current status, advantages, shortcomings and other related issues. The conclusion reached would comment on the future of green plastics and its scope as a replacement for petroleum based plastics.

Introduction

"Green", "Sustainable", "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, governmental agencies to educate people about advantages of going green have become common place. Corporate world is trying to show their commitment and investment towards 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 US economy is significant. According to the Society of 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

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grown at a rate averaging 3.4 percent. The U.S. plastics companies employ 1.1 million workers and provide nearly $379 billion in annual shipments [1].

Along with the growing plastics production and consumption so is a growing concern about its impact on the environment. The source for most commercial plastics is petroleum which is considered as a non renewable resource. Even though less than 5% of the petroleum is used in plastics manufacturing, the renewability of the source is often a concern as it takes millions of years for fossil fuels to be replenished. In addition, most of the commodity plastics such as 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 the landfill. Most of the commodity plastic materials are used for food packaging and therefore is either contaminated or difficult to clean for recycling. In addition, it cost 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 most growing sectors in Municipal Solid Waste (MSW) segment and 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, which leaves the fact that only less than 7% was recovered while aluminum and paper were recovered at a rate of 33.8% and 54.5% respectively [3]. Plastics manufacturers have been trying to reduce the flow of solid waste by source reduction, recycling at source etc. All such methods have its 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 poly lactic acid (PLA) are often projected as replacement for traditionally made petroleum based plastics such as polyethylene terephthalate (PETE), polystyrene (PS), polypropylene (PP) in commodities application. 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 first petroleum based plastics Phenol Formaldehyde (Bakelite) by Leo Bakeland, the history of bio based plastics took a twist. Since then bio plastics started merely getting sidetracked by petroleum based plastics. In 1920's Henry Ford, in an effort to find applications for agricultural surplus, experimented with manufacturing automobile parts from plastics made out of Soya beans [4]. The resin for soy plastics were not completely plant based whereas part of it was composed of phenol formaldehyde. Ford's soy plastic idea did not survive due to 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 Worlds War II the only non petroleum based plastic which was steadily growing in consumption was cellophane.

Definition of green plastics

The definition of green plastics has transformed far from the days of Ford's soy based plastics. Plastics are referred "Green" if they exhibit one or more of the following properties: source renewability, biodegradability/compostability after life and are 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 (one which degrades) or bio-based plastics (synthesized from renewable biomass) [5]. All biodegradable plastics are not bioplastics (some oil based plastics are biodegradable) and all bio based plastics are not biodegradable. Biodegradability of a material mostly depends on its chemical structure [6]. Plastics being a polymer, most of the oil based plastics have a strong carbon-carbon single bond which is difficult to break and 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 recyclable [7]. Green plastics are also referred as biopolymers. These natural polymers are inherently biodegradable because of the oxygen or nitrogen atom in their polymer backbones as opposed to carbon-carbon single bond for petroleum based polymers. According to 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 where as a compostable plastic undergoes biological processes to yield carbon dioxide, water and other inorganic compounds which are non toxic [8].

In the early years, renewability of materials mostly pointed towards the renewability of its source where as now it is redefined in terms of the carbon foot print it leaves. For example when comparing corn to sugarcane, both being source for ethanol, corn utilizes more fertilizer than sugarcane. The manufacture of fertilizers consumes natural gas thereby living large carbon foot print for corn [9]. Environmentally friendly nature refers to the direct and indirect impact the plastics has on the environment. This could be direct impacts during processing such as usage of water, amount of solid waste generated after life or indirect impact such as amount of electricity consumed, additional cost in transportation because of higher specific weight etc.

Green plastics are being widely publicized as a possible solution for concerns regarding the use of traditional petroleum based plastics. Several challenges could be faced in an attempt to replace petroleum based plastic products with green plastics. Physical properties, chemical resistance, processing, recycling, cost etc. are to name a few. These limitations have set the application of bioplastics to certain niche market accounting for 0.3% of global plastic production (according to 2007 estimates) [2]. But organizations such as European bioplastics, the industry association of the 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 polymer. This paper is a review of the current status of green plastics, major developments in the area, challenges faced. The conclusions reached would comment on the future of green plastics and its scope as a replacement for petroleum based plastics.

Green Plastics Classification

Based on the definition of green plastics in the previous section, E. S. Stevens classifies modern day green plastics into three categories [4]:
(i) Polymers extracted directly from biomasses (plants or animals), with or without modification (Referred Type I here after). For example polysaccharide starch modified polymers and polymers derived from cellulose.
(ii) Polymers processed directly by microorganisms through large scale fermentation process (Referred Type II here after). For example polyhydroxyalcanoates (PHA), copolymer of Polyhyrodxy butyrate and hydroxyvalerate (PHBV).
(iii) Polymers obtained from resins (monomers) produced with renewable and naturally occurring raw materials (Referred Type III here after). For example polyesters such as polylactic acid (PLA) processed from naturally occurring lactic acid monomer.

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

Table 1: Green Plastics Materials and Properties

Type	Origin	Examples	Products	Utility	Disadvantages	Advantages
Type I	Polymer extracted directly from biomass	Poly-saccharides (Starch)	Non Durable Goods: packaging, thin film bags	Medium	Modest strength, poor water resistance	Low cost
Type II	Polymer from large scale fermentation of biomass	PHBV	Durable Goods: Coating type I plastics for water resistance, blow molded containers, toiletry articles, office accessories	Low	High cost of synthesizing the polymer, Narrow melting range	Superior physical properties, good water resistance

Type III	Monomer extracted from biomass	PLA	Non Durable goods: Disposable Plates, cups, boxes, film wraps	High	Low thermal resistance, brittleness, high specific weight	More cost effective than Type II, optical clarity, good moisture resistance

Processing Green Plastics Products

Products made of biodegradable plastics must be stable during processing. Most of the green plastic materials are processes by methods such as thermoforming, injection molding, blow molding and extrusion [12]. These processes demands mechanical and physical properties such as melt strength, flow, elongation, temperature resistance, elasticity. Most of the green plastic materials have property issues such as modest strength, low water and temperature resistances, lower impact strength etc. Therefore these materials requires improvement and modification and hence most commercial bioplastics are composed of several chemicals such as additive stabilizers, colorants etc which makes it almost impossible to be manufactured from 100% renewable resources (most of the bioplastics now contains 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 market place from compostability to renewability partly due to lack of infrastructure here in the United States [14].

Higher specific weight of commonly used bioplastic materials such as PLA is always an issue. PLA, often used in packaging, has a high specific weight (1.24g/cc) compared to PP (.90 g/cc) and PS (1.04g/cc) which implies more material usage and processing cost for a given packaging. PLA also has lesser resistance to prolonged temperature exposure over 130F [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 R&D compared 16-0z drink cups, deli containers, envelop window film, foam trays and 12 oz containers made using PLA with ones made using equivalent PET and PP [16]. The study observed total energy consumed, solid waste generated and green house gases emitted during the manufacture of the above mentioned products. From fabrication to grave most of the PLA packaging consumed generated more solid waste and consumed more energy for production. The more 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 out that PLA will be difficult to degrade in all house hold compost pits and would emit comparable amount of green house gases as 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 the advocates argues that the additional crops cultivated to produce green plastics would remove substantial amount of carbon dioxide from the atmosphere.

Most biopolymers seems to be tough to process because there is very little 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 challenge in injection molding bioplastics is heat, moisture, and degradation caused by excessive temperature, shear or residence time [17]. Modification needs 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 longer time and therefore would require higher cooling time. It 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 (low as 250ppm) would 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 needs 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. Besides PLA's higher tensile strength and lower elongation properties could make thermoforming difficult [19]. Other obstacles while thermoforming PLA includes its low melt strength which could cause shearing when stretched.

Recycling Issues

Plastics recycling fall into two categories: pre-consumer and post-consumer [20]. Pre-consumer one involves recycling of waste generated while manufacturing 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 considerable amount of cleaning and sorting activities. Within the petroleum based plastics it is not easy to determine the difference 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 an unusable recycled plastic for many processes. This is very likely to happen as the consumers may not differentiate between different plastic types. Therefore bioplastics should be from identifiable sources that will allow for sorting. Currently in the United States, very less infrastructure exist to collect bioplastics in sufficient quantities and consumers do not have a clear picture on its recyclability. Another option of dealing 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 not true. In fact anything that goes into a landfill (bioplastics or oil based plastics) will not decompose properly because or the lack of sunlight and air. Therefore composting bioplastics needs additional infrastructure and setting to handle the volume. Commercial bioplastics such as PLA would 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 bioplastics composed of starch and other synthetic polymers which are fully biodegradable [22]. Blending can overcome property shortcoming such as water resistance, strength, and elasticity. BASF's Ecovio, which is fully biodegradable, is another example of synthetic blending where 45 percent Naturework's PLA (made from lactic acid) is combined with 55 percent 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 that makes it a suitable material for packaging materials and other non durable goods. Starch based biopolymers have poor water resistance and modest strength. In order to overcome these short comings 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 (upto 85%) with conventional plastic monomer to produce a synthetic blend which is claimed to have better thermal properties and shape memory properties [2]. Now a question arises that some of the synthetic materials may have a non renewable source resulting in not so 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]. ASTM D-6868 specification covers biodegradable plastics and products (including packaging), where plastic film or sheet 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 internationally such as 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 specification and standards for compostability (based on ASTM D6400 and D6868), complying upon will the product be eligible to use the BPI logo. Similarly in Japan, Japan Bioplastics Association (JBPA) has started the BiomassPla certification to distinguish products made from biomasses [24]. Certification from 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 bioplastics industry as studies in Europe and Japan has shown the consumer willingness to spend the extra dollar for sustainable products [25].

Cost Factor

Cost is a significant factor when it comes to most plastics application especially disposable ones such as packaging. For example if a small bag of chips from a vending machine cost $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 the recent years. For example PLA which cost $3/lb in 1990's has dropped to 90cents/lb in 2010. The rise in oil price has made bio based plastic prices comparable to the price of oil based commodity thermoplastics. But still additional cost incurred due to increased processing steps and high specific weight and several other factors could be impediments to the bioplastics usage. Along with the growing concern on utilizing agricultural land for production of bio raw materials such as corn, one of the other obstacles for growth of bioplastics would be 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 on agricultural land may not be an issue. But according to Evans if bioplastics grows to almost 10% then that will require 5 billion pounds of starch which could make an impact on agriculture. Also the increased use of crops such as corn for ethanol has doubled its price in the past one year [2].

Conclusions

Current market trends look promising towards the growth of bioplastics. Significant growth has been observed in patents deposit for bioplastics such as PLA which had 20 deposited in 1998 versus 330 in 2005[10]. The bioplastics industry demand is expected to hit an annual production of 2% of global thermoplastics production which is approximated at 250 million tons annually. Major manufacturers and even governments are focusing on renewability of the plastics. For example, the Japanese government has set a target that by year 2020 20% of their plastic production will be from renewable sources. Toyota targets to make 20% of their interior trims from renewable source by 2020. Ford is currently using soy based polyurethane on seats of twenty-three of its models. Consumer Product Giant P &G has it long term goal set to making all its packaging renewable or recyclable and replacing 25% of 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 processing, material properties and recycling challenges faced while attempting to replace the petrochemical based plastics. Most of the bioplastics currently are utilized for non durable goods such as packaging. Plastics such as PHA has comparable properties to that of petroleum based counterparts and could be used for durable goods. The fermentation step in processing makes the raw material expensive. Research is underway to process such polymers without fermentation [22]. Green plastics with a wide range of properties that could allow them to be processed like conventional plastics needs to be developed. One of the real problems that exist is in defining and identifying green plastics. There needs to be a better understanding of what constitutes greenness. A venture between governments, industry and the society (such as BPI) could play an extensive role in educating the society 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 to focus their efforts towards attaining a common target. Infrastructure for collection and composting of degradable plastics needs to be improved. Governmental incentives such as tax cuts and rebates could also help to promote greenness. Diversification of feed stocks from food crops to alternate biomass materials could have a positive impact on the cost as well as concern for using agricultural land. There seems to be a lot of enthusiasm among the society, industry and the governments 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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