Sustainability of Bio-based Plastics: General Comparative Analysis

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Abstract

This study evaluated the sustainability of bio-based plastics including all the stages of their life cycle (cradle to grave) to assist in decision-making about selection of these bio-based materials. Plastics are considered essential materials in today's society, but during their life cycle they contribute to pollution and depletion of natural non-renewable resources. Bio-based plastics appear as more environmentally friendly materials than their petroleum based counterparts when they are compared considering their origin and biodegradability. But which of the bio-based plastics currently on the market or soon to be on the market are preferable from an environmental, health, and safety perspective? Results of this study were summarized in two graphic tools based on analysis of the data gathered on bio-based plastics according to sustainability criteria. They showed that none of bio-based plastics currently in commercial use or under development are fully sustainable. Each of the bio-based plastics reviewed utilizes genetically modified organisms for feedstock manufacture; toxic chemicals in the production process or generates as byproducts, or co-polymers from non-renewable resources, etc. Substitution of conventional petroleum-based plastics with safer bio-based plastics requires the knowledge of the flow of these materials and their adverse impacts in all their life cycle in order to consider new approaches towards sustainability.

Keywords: *Bioplastics, bio-based plastics, life cycle analysis.*

1 Introduction

Plastic materials are considered the most important materials in this time due to their exceptional properties and performance over other materials such as metal and wood (Aguado and Serrano, 1999; Azapagic. et al, 2003; Rosato and Rosato, 2003; PlasticsEurope, 2008). The projection is that the demand of plastics will continue following the increasing trend that they have shown since the 1950s (PlasticsEurope, EUPC, EPRO, EuPr, 2008). Having plastics materials such importance in our society and knowing that materials are a fundamental determinant of sustainability (Geiser, 2001); currently the substitution of petroleum-based plastics with bio-based plastics is seen as a promissory alternative because it will also reduce the dependency of plastics on fossil fuels and the pressure in landfills from plastic solid wastes. Development and commercialization of bio-based plastics for a variety of uses in products and packaging is also of great interest as manufacturers are looking for safer and healthier materials as substitutes for chemicals and materials of concern in consumers' products. Bio-based materials are promising as their feedstocks are renewable, theoretically they can be composted or recycled, and their production process can be more energy efficient than petroleum-based plastics processing.

This study starts the process to provide an insight of the health and environmental impacts of the sustainability of bio-based plastics considering that sustainable materials are those that during their life cycle reduce impacts to occupational and public health as we all to the environment (Geiser, 2001). Therefore, the aim of this study was evaluate the general sustainability of different bio-based plastics based on an extensive review of literature and considering environmental, health and safety impacts during their life cycle through the development of a graphic tool to assist in decision-making about bio-based plastics selection.

2 Metodology

An extensive literature review and manufacturers provided information of the bio-based plastics more commercially developed or prone to be in the market. They were polylactide acid (PLA), starch (pure thermoplastic starch: TPS), polyhydroxyalkanoates (PHAs), poly(trimethylene terephthalate) (PTT), ligno-cellulosics, plastics from corn and soy protein, bio-based urethanes (BURs) and nano-biomaterials. These bio-based plastics were defined and described according to their source, production process, properties, process techniques, uses, environmental, health and safety impacts, costs, and commercial readiness.

In order to define a sustainable plastic, a review of ranking schemes and criteria that have been developed in the last decade to aid in decision-making was done. The Principles for the Sustainable Biomaterials Collaborative (SBC, 2009) was used as a framework to develop a definition for sustainable plastic in this study and to make the evaluation of the sustainability of the bio-based plastics from the information obtained in the literature review. The sustainability criteria included the environmental, health and safety impacts during the life cycle of the plastics, for example, use of genetically modified organisms (GMOs) and hazardous pesticides to grow the feedstock to produce the bio-based plastic; use of hazardous chemicals or petroleum-based co-polymers during plastic production and processing; hazardous additives or untested nano-materials; potential hazards in workplaces, disposal options, potentially impact to food supply, efficiency in the use of water, energy, and materials, etc. Each bio-based plastic was reviewed according to sustainability criteria.

The limitations of this study are related to the development of bio-based plastics. The industrial production, research and commercialization in of these materials are very competitive. Therefore, any development and innovation in the field lacks specific details due to the research and commercial interests. Bio-based plastics are still in its infancy and there is scarce information about environmental, health and safety impacts during their life cycle. For example, there are only comprehensive life cycle assessment (LCA) for some starch polymers, for PLA and PHAs there are few limited studies that involve only use of energy and greenhouse gases. There are no LCA studies for other bio-based polymers. Evaluation of sustainability of bio-based plastics will be done with the isolated information currently available and knowing that continuous research and improvements in this field may change the results obtained here in the future.

3 Results and Discussion

The Principles for Sustainable Biomaterials (SBC, 2009) provided a useful framework for evaluating the bio-based plastics currently being commercialized. The Bio-based Polymer Spectrums for Occupational Health and Environment showed in Figures 1 and 2 summarize the analysis of the data gathered on bio-based plastics according to sustainability criteria and provide a visual comparison of the bio-based plastics. Bio-based plastics that are preferred from a sustainability perspective will utilize a feedstock grown without GMOs and without hazardous pesticides; will be processed without GMOs, hazardous chemicals or petroleum-based co-polymers; will avoid hazardous additives or untested nano-materials; will address environmental and safety hazards during their production; will not impact food supply, will show flexibility for disposal, it can be compostable, recyclable, and in the case of landfilling and incineration or (least recommended options), it will not generate toxic emissions; and will be energy and water efficient in production and will avoid generation of byproducts.

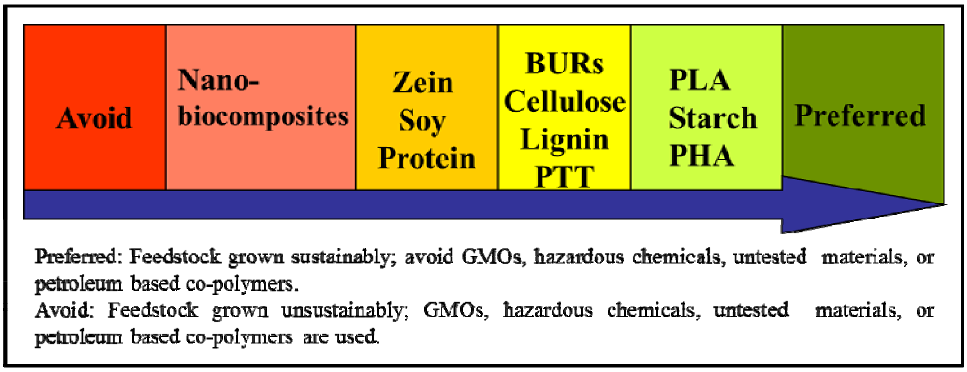

Fig. 1. The Bioplastics Spectrum. Comparative occupational health and safety impacts of bioplastics. BURs: bio-urethanes; PHAs: polyhydroxyalkanoates, isolated and purified by enzymatic methods; PTT: poly(trimethylene terephthalate). GMOs: genetically modified organisms.

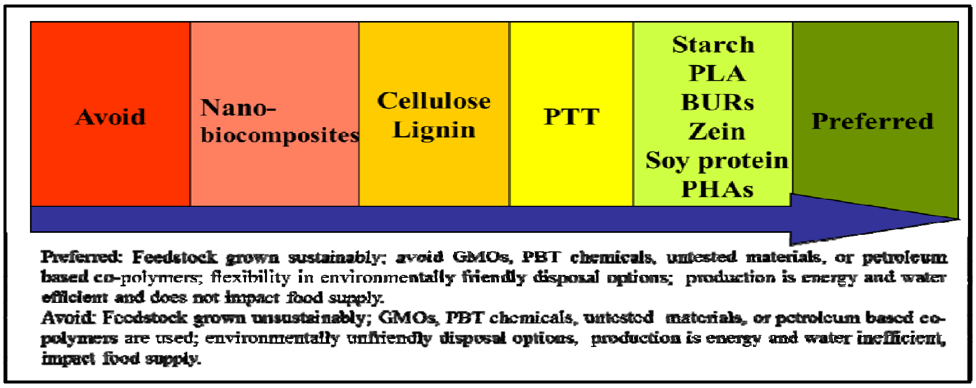

Fig. 2. The Bioplastics Spectrum. Comparative environmental impacts of bioplastics. BURs: bio-urethanes; PHAs: polyhydroxyalkanoates, isolated and purified by enzymatic methods; PTT: poly(trimethylene terephthalate). GMOs: genetically modified organisms; PBT chemicals: persistent bioaccumulative and toxic chemicals.

3.1 Comparative Analysis Considering Occupational Health and Safety Impacts

Despite bio-based plastics claim to be more environmentally friendly the fact is that there are occupational hazards in their production. Common health potential hazard in the production of bio-based plastics are the use of pesticides during the production of crops and the use of GMOs.

The health and safety impact analysis (Figure 1), found that PHAs, PLA, and starch (TPS) (light green) are preferred to the other bio-based materials. Although there are some occupational hazards in their production, these hazards were considered lower than that of the other bio-based materials. They also are fully bio-based, rather than containing a petroleum-based component.

3.1.1. PHAs. They are aliphatic polyesters produced via fermentation of renewable feedstocks such as sucrose, vegetable oils and fatty acids. More recently, they have been experimentally produced from waste left over from the production of ethanol from the stalk and leaves of corn plants (Yu and Chen, 2008). PHAs pose safety hazards for workers if physical extraction or chemical digestion methods (Hocking. and Marchessault, 1998) are used to isolate and concentrate them. The enzymatic hydrolysis method is the safest method for workers as it does not require the use of toxic chemicals.

Physical extraction of PHA may expose workers to halogenated solvents including chloroform, methylene chloride, and 1,2-dichloroethane (Hocking and Marchessault, 1998). These chemicals are considered occupational carcinogens by NIOSH and IARC has classified them as 2B, possibly carcinogen to humans (NIOSH, 2009a; NIOSH, 2009b; NIOSH 2009f; IARC, 2008). Other chemicals that may be used include pyridine, methanol, hexane or diethyl ether (Hocking and Marchessault, 1998). Pyridine is flammable and causes eye irritation, headache, anxiety, dizziness, insomnia, nausea, anorexia, dermatitis, liver, and kidney damage (NIOSH 2009g). Methanol is flammable and causes eye, skin and upper respiratory system irritation, headache, drowsiness, dizziness, nausea, vomiting, visual disturbance, optic nerve damage (blindness), and dermatitis (NIOSH, 2009e). Hexane is flammable and causes eye and nose irritation, nausea, headache, peripheral neuropathy (numb extremities, muscle weakness), dermatitis, dizziness, and chemical pneumonitis (aspiration liquid) (NIOSH, 2009d). Diethyl ether is flammable, can produce explosive peroxides in contact with oxygen under storage conditions and causes irritation in eyes, skin, upper respiratory system, dizziness, drowsiness, headache, narcosis, nausea, and vomiting (NIOSH, 2009c).

Chemical hazards of the chemical digestion method include sodium hypochlorite, methanol and diethyl ether (Hocking and Marchessault, 1998). Sodium hypochlorite has a pronounced irritant effect and may cause severe burns to skin and eyes. Poisonous vapor (chlorine gas) is corrosive to respiratory passages and may cause irritation of mouth, nose and throat. If ingested sodium hypochlorite is poisonous, causes burns, abdominal cramps, nausea, vomiting, lowered blood pressure, diarrhea, shock, coma, shock, and death may occur (ATSDR, 2010a). Hazards of methanol and diethyl ether are described above.

3.1.2. PLA and Starch. PLA is a thermoplastic aliphatic polyester obtained by the polymerization of lactic acid derived from microbial fermentation of corn starch or cane sugar (Vink, 2008). Pure thermoplastic starch (TPS) is obtained without fermentation or chemical treatment of natural corn, potato, rice, tapioca or wheat starch which are extruded or blended to produce TPS (Crank et al, 2005). Therefore, both bio-based plastics can impact food supply. Starch may be used in plastics blended with synthetic polymers (25-40% conventional polymers), or as a thermoplastic (75–95% starch) (Moran, 2002).

Potential health hazard in PLA and starch is the use of GMOs in crops to produce higher yields or to improve starch properties (Ahmann and Dorgan, 2007). Statistics show an increasing trend of all biotech corn hybrids planted; in 2008, 85% of acreage in the United States was planted with bioengineered corn (NASS, 2010). Bioengineered microorganisms used in the production of plastics from starch are of concern because ecosystem impacts from GMOs are not well understood (Graedel and Howard-Grenville, 2005, Hammond, 2010). PLA can also use GMOs during fermentation of glucose (Clark and Hardy, 2004).

The production of starch poses safety hazards for workers as starch in a finely pulverized form can suspend in the atmosphere and cause powerful explosions (OSHA, 1996). PLA production uses sulfuric acid during the recovery of lactic acid from fermentation broth and organic tin in the polymerization catalytic system (Clark and Hardy, 2004, Crank et al, 2005, Vink et al, 2003). The use of sulfuric acid, a highly corrosive substance (PTCL, 2010c), and tin based catalysts, is an issue for the health and safety of the workers in the newly emerging PLA industry. During the industrial manufacturing of PLA, organotin based catalyst system (tin octanoate) is used in very low concentrations (100-1000 ppm) (Henton et al, 2005). OSHA has reported that the hazards of using $Sn(Oct)_2$ in workplaces are related to the hazards of organic tin compounds (NIOSH, 1978). Organotin compounds have showed neurotoxic effects in animals and cytotoxic effects in human and animals and can affect sex differentiation, resulting in masculinization of females or infertility in male aquatic animals (Shi et al, 2009; Yamada and Takashi, 2008; Tanzi, 1994; Grun, 2006). The toxicologic mechanism for organotin compounds is not completely understood and the essential cellular target of organotins has not been identified ($Sn(Oct)_2$). 1-Octanol is also used in the ring opening catalysis step to control molecular weight and accelerate the reaction (Södergård and Stolt, 2002; Drumright, 2000). 1-octanol is a volatile and combustible liquid that can be absorbed into the body by contact, inhalation, and by ingestion causing irritation to the tissues. Since the vapors of 1-octanol are combustible, fire is a hazard in workplaces (Mallinckrodt Chemicals-Jt Baker, 2009). 1-octanol is slightly toxic to fish and zooplankton (Kegley et al, 2010).

Glycerol and urea are used in TPS as plasticizers (Crank et al, 2005). Glycerol and urea are considered a low hazard for normal industrial handling or normal workplace conditions (PTCL, 2006a; PTCL, 2005e; Science Lab.com, 2010b).

3.1.3. Bio-urethanes (BURs), cellulose, lignin and PTT. BURs are obtained by the reaction of isocyanates with the diol or polyol groups present in vegetables oils such as castor, soy, sunflower and linseed. Cellulosic and lignin plastics are produced by chemical modification of natural cellulose and lignin obtained from wood and short cotton fibers called linter. PTT is a linear aromatic polyester produced by the reaction of 1,3 propanediol (PDO) and a dicarboxylic acid such as terephtalic acid (PTA) or dimethyl terephthalate (DMT). PDO can be obtained by microbial fermentation processes from glucose of corn starch, whereas PTA and DMT are petroleum-based feedstocks (Crank et al, 2005).

There are numerous different types of BURs, cellulose and lignin plastics therefore to address hazards of their production process is difficult. BURs, cellulose and lignin plastics, and PTT are light yellow because they may use hazardous chemicals during their manufacturing.

Producing BURs require the use of hazardous isocyanates (Crank et al, 2005). Toluene diisocyanate (TDI) is a very volatile liquid that is a severe irritant to mucous membranes of the eyes and respiratory tract. Acute exposure to TDI can cause euphoria, ataxia, and mental aberrations. Very low subsequent inhalation exposures to TDI have caused asthma attacks in workers. High dose exposure to

TDI by inhalation can lead to chest tightness, coughing, breathlessness, inflammation of the bronchi with sputum production and wheezing, and non-cardiogenic pulmonary edema (ATSDR, 2010b). TDI is classified by the International Agency for Research on Cancer as possibly carcinogenic to humans. Because of concerns about the carcinogenic potential of TDI, methylene diphenyl isocyanate (MDI) is often used as an alternative. MDI can irritate the skin, eyes and respiratory tract. Chronic exposure to MDI can sensitize the skin or respiratory tract, which may lead to asthma (Scorecard, 2005a).

The conventional production of cellulose by kraft pulping of wood involves the use of elevated temperature, pressure and harsh chemical treatment with sodium sulfide and sodium hydroxide (EPA, 2010). Lignin is a by-product of this process. Sodium hydroxide and sodium sulfide are strong corrosives (NIOSH, 2010; PTCL, 2006b; PTCL, 2010b). Hydrogen sulfide, methyl mercaptan, dimethyl disulfide, and other volatile sulfur compounds are highly flammable, toxic and malodorous air emissions byproducts (Bordado and Gomes, 2003; IPCS, 2005; PTCL, 2005a; PTCL, 2005b). These chemicals pose acute exposure hazards to workers.

Cellulose acetate is made by reacting cellulose with acetic acid; cellulose acetate butyrate is made by treating fibrous cellulose with butyric acid, butyric anhydride, acetic acid and acetic anhydride in the presence of sulfuric acid. Cellulose acetate proponiate is made by treating fibrous cellulose with propionic acid, acetic acid and anhydrides in the presence of sulfuric acid (Crank et al, 2005). Cellulose nitrate is made by treating fibrous cellulosic materials with a mixture of nitric and sulfuric acids. All of these chemicals have the potential to produce mild to severe irritation of skin, eyes and respiratory tract (Celanese, 2008; PTCL, 2005c; PTCL, 2005d; PTCL, 2010a; PTCL, 2010c; Science Lab.com, 2010a).

PTA used during the polymerization process of PTT is a suspected neurotoxicant (Scorecard, 2005b). DMT can also be used for polymerization of PTT, as an alternative to PTA. DMT is considered a low hazard in workplaces because of its low volatility, however accidental dermal contact is of concern from possible burns from molten liquid (melting point is 141 °C) (OECD. SIDS, 2001).

3.1.4. Zein (Corn Protein) and Soy Protein. Proteins have a complex structure with many sites that can interact with plasticizers and other polymers to be converted into plastics through an extrusion process (Ahmann et al, 2007). They are dark yellow because they may use corrosives and carcinogens in their production process. The production of plastics from proteins can impact food supply and involves the use of flammable chemicals like alcohol or other volatile solvent, as well as alkaline and acid substances that are corrosives. Formaldehyde or gluteraldehyde are used as a crosslinking agent (Guilbert and Cuq, 2005; Ly and Johnson, 1998). Formaldehyde is carcinogenic to humans; chronic exposure to glutaraldehyde can cause skin sensitivity resulting in dermatitis, irritation of the eyes and nose and occupational asthma (Cogliano et al, 2005) (OEHHA, 2007).

3.1.5. Nano bio-composites. They are obtained from natural fibers such as cellulose (Ahmann and Dorgan, 2007). They are orange because pose unknown risks. The health effects of nano-particles are of concern because their impacts are not well understood. Toxicologists hypothesize that nano-particles may not be detected by the normal defense system of organisms. Their small size can modify protein structures, and they can travel from respiratory system to the brain and other organs (Levy et al, 2006).

3.2. Comparative Analysis Considering Environmental Impacts

Bio-based feedstocks are generally grown using methods of industrial agricultural production and therefore significant amounts of energy, water, land, toxic pesticides and fertilizers are used, which deplete natural resources, can pollute water, air and soil. The environmental analysis (Figure 2), found that starch, urethanes, PHA, zein, and soy protein (light green) are preferred although GMOs of unknown hazards and PBTs (pesticides) may be used in feedstock production. Advances in biotechnology make it possible to produce plastic directly in microorganisms or in genetically modified crops such as corn. The use of GMOs in the development of bio-based plastics is a concern, because their effect in the environment is not well understood (Hammond, 2010).

PLA manufacture uses organic tin and 1-octanol during lactic acid polymerization (Ahmann and Dorgan, 2007: Södergård and Stolt, 2002; Drumright, 2000). Small residues of organic tin in PLA products can be a concern during disposal because it has lipohilic properties and can build up on aquatic organisms and plants and it has also been found in human tissues (Shi et al, 2009). According to manufacturers, burning and landfilling PLA des not generate toxic emissions and leachates (Vink, 2008). 1-octanol is slightly toxic to aquatic organisms (Kegley, et al, 2010). According to a life cycle assessment carried out by Vink et al (2003), PLA used 30-50% less fossil energy and resulted in lower CO_2 emissions by 50-70% compared to petroleum based plastics. More recently, a new ecoprofile showed 85% less CO_2 emissions and 50% less fossil fuel use compared with data of 2003 (Vink et al, 2007).

PHA was ranked as light green, assuming it is isolated and purified using the enzymatic method (other methods require hazardous chemicals) (Crank et al, 2005, Tullo, 2008) Data on energy requirements of PHA production is controversial (Crank et al, 2005), however, PHA's manufacturers reports that the manufacturing of these bio-based plastics uses 3.5% the energy required to make conventional plastics (Tullo, 2008). PLA, thermoplastic starch, PHA, zein, and soy protein are biodegradable and compostable (Ahmann and Dorgan, 2007, Flieger, et al, 2003, Vink, 2008). Data about the compostability of BURs were not available. PTT production (light yellow) is energy efficient, can be potentially recycled, PTT scrap is usually classified as non-hazardous waste and can usually be landifilled or burned, but uses terephthalic acid (PTA) or dimethyl terephthalate (DMT) as feedstocks, which derive from petroleum. Cellulose and lignin are obtained using traditional method of pulping (kraft process), which requires large amounts of energy and water, uses harsh chemicals such as sodium disulfide and sodium hydroxide and generates large amounts of wastewater and greenhouse gases (dark yellow) (EPA, 2010). Nano- biocomposites (orange) pose unknown risks.

4. Conclusions

The conclusions of the evaluation and comparative analysis of the sustainability of bio-based plastics according the sustainability criteria is that none of bio-based plastics currently in commercial use or under development are fully sustainable. Some bio-based plastics are preferable from a health and safety perspective and others are preferable from an environmental health perspective. In general, with the specified criteria; starch, PLA, PHA polymers score better than other bio-based polymers.

The production process of bio-based plastics is not hazard-free. Bio-based feedstocks are generally grown using methods of industrial agricultural production and therefore significant amounts of toxic pesticides are used, which can pollute water and soil, and impact wildlife habitats. When processing bio-based feedstocks to produce plastics, significant amounts of energy and water are used, as well as hazardous chemicals/additives, genetically modified organisms (GMOs) or engineered nano-materials. Occupational health and safety hazards are also present during the growing and processing of feedstocks. Biodegradability of bio-based plastics is affected when bio-based polymers are co-polymerized with petroleum-based compounds, and infrastructure for composting is not available.

The Bioplastics Spectrums for Health and Environment were developed in this study, as a tool to assist in decision making-about their selection based on the sustainability criteria. The placement of the bio-based polymers in the may change as additional data becomes available.

This study is an effort to start providing information about the potential environmental and occupational and public health impacts of bio-based plastics which results in a more comprehensive approach in the study of their life cycle in terms of sustainability.

Biodegradable plastics have the potential to reduce the use of fossil fuels and related environmental and health impacts and to avoid non-degradable and bulky plastic wastes. However, the use of biodegradable plastics brings new challenges that are present during their whole life cycle. More research is needed to produce novel environmentally friendly and safer plastics, but it is also necessary to create the required infrastructure and new policies to address the range of issues surrounding the sustainability of the bio-based plastics industry.

At last, the current global food crisis has raised serious questions about the use of agricultural land to grow crops for industrial products such as ethanol. Research to develop a second generation of bio-based plastics from sources that do not compete with food production, such as byproducts of agriculture (corn straw, grasses) and wood is imperative.

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