THE GREENING OF 'GREEN' TECHNOLOGY: ADOPTION OF BIO-PLASTIC PLA

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Abstract: Growing concerns over the impact of rising commodity prices on the global food system has led to a vigorous public debate over the use of plant materials as fuel alternatives. Despite this controversy, several bio-based technologies are being promoted as sustainable materials. This paper examines one such technology - Bio-plastics Polylactic Acid - that is being adopted at a rate that is higher than convention plastics, although energy efficient this technology is still not cost effective. High adoption is most likely driven by disincentives created by end-use packaging legislations and also short-term concerns for the environment. Two important log-term concerns that are highlighted are divergence between technical and economic superiority and market failure. Thus the main drivers of adoption in the long-run are expected to be declining production cost, environmental legislation concerning waste disposal and composting, and consumer attitudes towards environmental impact.

Keywords: Sustainable materials, Adoption, Bioplastics, Polylactic acid, Market failures

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1. Introduction

Historically high oil prices of US $147 per barrel were reached in 2008. High and volatile crude oil prices provide an economic incentive to businesses and households to adopt alternative to oil, such as plant materials for energy production, including bio-fuels (Vedenov *et al.*, 2006; Harrison, 2009), and production of other 'sustainable' materials, such as bio-plastics. However, growing public concerns over the impact of rising commodity prices on the global food system has led to a vigorous public debate over the use of plant materials for fuel production (Rajagopal *et al.*, 2007). Similar arguments hold for their use as alternative feedstocks for the production of other 'bio' materials. Food and oil prices are linked to one another, particularly through the use of significant amounts of energy to produce nitrogen fertilizer. At the same time as the oil price peaked, corn prices recorded an all time high of $4.20 per bushel and prices of other grains were also historically high. Both high oil and grain prices had a significant adverse impact on the poor in developing countries (Elobeid and Hart, 2007). They also led to the assertion that using food grade plant material as feedstock for industrial processes was an important determinant of high food prices.

Despite this controversy, bio-based technologies are being promoted as sustainable alternatives to those based on fossil fuels (Van Dam *et al.*, 2005); with some success. The global consumption of biopolymers, especially the biodegradable polymers, increased from 14 million to 68 million kg between 1996 and 2001 (Gross and Kalra, 2002). One reason, frequently cited

for why bio-based technologies are being endorsed, is because of fossil energy savings, another is because their use reduces greenhouse gas emissions and thirdly, bio-based technologies increase security of energy supply (Gomes et al., 1997; Rajagopal and Zilberman, 2008). Sheridan (2009), for instance, suggests that even a partial transition from fossil fuels to biomass-derived alternatives could substantially reduce greenhouse gas emissions in transportation and chemical production.

Policy regulation is a significant contributor to increasing interest in bio based technologies. In the United States (US), geopolitical as well as environmental considerations are behind the drive to reduce fossil fuel consumption. As part of this, the US Department of Energy has set goals to replace 25 percent of industrial organic chemicals with biomass-derived chemicals by 2025 (Chum and Overend, 2003). To achieve this goal, the US ethanol production is supported by both tax credit ($0.51 per gallon) and an import tariff ($0.54 per gallon) (Rajagopal et al., 2007). Similar motivations underlie the European Union Directive 2003/30/EC adopted in 2003. This targeted 2 percent and 5.75 percent of all petrol and diesel transport fuels to be biomass-derived by December 2005 and December 2010, respectively. A recent directive by the Commission, while showing that only Germany (3.8%) and Sweden (2.2%) reached the reference level of 2% in 2005, states that it is unlikely that member states will achieve the 5.75% by 2010 (Commission of the European Communities, 2007).

To date analysis of the technical and economic costs and benefits of sustainable technologies to underpin policy has been largely confined to bio fuels (e.g., Rajagopal and Zilberman, 2007). Analysis of the contribution of several other products that are being developed from biomass as alternatives to fossil feedstock is much less well developed (Ragauskas, et al., 2006). The current

literature has tended to ignore some of these important developments. The aim of this paper is to fill one of the many gaps in the literature. This is the extent to which the nascent development of making plastics from plant materials has the potential to replace plastics traditionally made from fossil fuel oil. Were this to happen, it would impact on a wide range of industrial applications, such as packaging, clothing, etc. The relevant questions concerning the development of bio-plastics address the issues of sustainability, comparative technical performance, and economic superiority/inferiority of plant over oil based plastics.

Plastics and polymers are essential elements of modern life. The current global consumption of plastics is more than 200 million tonnes, and that production is increasing at a rate of approximately 5 percent per year (Vink *et al.*, 2003; Siracusa *et al.*, 2008). This in part, reflects the fact that plastics represent the largest field of application for crude oil. Bio-plastics, like plastics, therefore present a large spectrum of potential applications, such as collection bags for compost, agricultural foils, toys, fibres, textiles, packaging, etc. Making plastics out of plant materials rather than oil would advance significantly global progress towards sustainability.

The rest of the paper is organized as follows. In section II, we re-examine the concept of sustainable materials as currently defined and examine different technologies that are currently being developed as alternatives to fossil based plastics. Only two such materials meet our definition of sustainable material technology. These are polyhydroxyalkanoates (PHA) and polylactic acid (PLA). Only one, PLA, constitutes a close substitute, in terms of technical performance to an equivalent oil based plastic, i.e., polyethylene terephthalate (PET). In section III, we examine the interrelationship between the production of PLA and alternative uses of corn, including as a source of food. Section IV assesses to the extent to which PLA is a close substitute

for PET, in terms of key material performance requirements based on technical aspects of PLA technology. Section V examines the comparative economic aspects of PLA and PET, including adoption, market share and cost effectiveness. In the next section, we examine potential alternatives that could make PLA more cost-effective. The last section concludes.

2. Defining sustainable materials

The last few years have seen the emergence of several new plant based technologies that claim to provide a sustainable alternative to fossil fuel based products (Ragaukas, et. al., 2006; Sheridan, 2009). The validity of these claims has yet to be subjected to robust close scrutiny. In this section, we re-examine the concept of sustainable materials as currently defined, and examine different technologies that are currently being developed as alternatives to fossil based plastics. As the world shifts away from dependency on petroleum resources, it is imperative that clear and accurate perceptions of the sustainable alternatives are recognized. Progress to validation is not helped by confusion over the definition of sustainability, and its application to the classification of which materials provide sustainable alternatives. Like many other examples of emerging ideas, convergence on a widely accepted definition of sustainable material is an empirical and iterative process. This takes time. The diversity of views in the literature indicates that consensus as to the meaning of sustainable materials still lies some way off. The result is sustainable materials have been defined in so many ways that the term can seem like it means all things to all people.

Clarity of definition certainly aids understanding. Sustainable development is formally defined by the World Commission on Environment and Development as "development that meets the needs of the people today without compromising the ability of future generations to meet their

own needs" (Bruntland Report, 1987). Sustainable products have been defined as bio-based products which are derived from renewable resources, could be recycled, biodegradable and all in commercially viable ways. (Mohanty *et al.*, 2002). But this definition raises a lot of questions. What is meant by recycling and how restrictive are the conditions that need to be in place for recycling to take place. There are often large divergences between ideal and practice. Costs of collection of recyclable material are high relative to other ways businesses, households and government spend their money. Some plastics are only recyclable if they are melted at very high temperature. If there is residue left in the ground after a material has biodegraded, should this be treated as partial rather than full biodegradability. Some of the recently developed biobased industrial products are liquid fuels, chemicals, lubricants, plastics and building materials.

Not all technologies that are based on renewable resources, such as plants, are necessarily sustainable. Energy consumed during conversion and greenhouse gas emissions, from crop production to ultimate disposal or recycle, all mean that some plant based products do not conform to the above definition of sustainability. Even if it were possible to agree on a definition of a sustainable material there is also considerable debate over the translation into the most appropriate indicators and means of quantification. A widely advocated approach for measuring sustainability of energy use and gas emissions is life cycle assessment, a valuable tool with several caveats (Ferrell *et al.*, 2006; Rajagopal and Zilberman, 2007).

This variability in approach to definition of sustainability and the different criteria used is illustrated in table 1. What should be the basis of a definition of sustainable material technology? Following convention, we take the view that the basis of any definition has to be that the key distinctive features when combined in one object mean that it can be distinguished from other combinations of other features in another object; in ways that aid understanding. Since very few

objects are the same in all respects, any definition must contain some element of generalisation. The issue is the selection of what are regarded as the key aspects of sustainable materials technology. We assert that these are the elements that are of greatest interest to governments, businesses and households. We propose that the key aspects of greatest interest are (Table 1):

- Technologies with feedstocks from a renewable source;

- A product from renewable source which can be reused;

- Products that can both be recycled at low cost and minimum energy and are either biodegradable or non-biodegradable can be treated as sustainable materials,

The choice of these criteria mean we are excluding from our classification of sustainable material technologies non-recyclable products, both biodegradable and non-biodegradable that are disposed of via landfill or incinerated. Several thousands of tons of goods, made of plastic materials, are sent to landfill, increasing every year the problem of municipal waste disposal (Kirwan and Strawbridge, 2003), and emitting methane and carbon dioxide into the atmosphere (Galle *et al.*, 2001). Consequently, biodegradability is not only a functional requirement but also an important environmental attribute (Siracusa *et al.*, 2008). Similarly, we also exclude all non-renewables, even if recyclable, because they have fossil fuel origin.

Table 2 shows the results of applying these criteria to different bio-based polymers given their known respective attributes. The basis for inclusion in the table are the polymers either commercialized or on the verge of commercialization. The result is that only two of the fourteen materials currently developed conform to our proposed definition of sustainable material technology. Materials such as polytrimethylene terephthalate (PTT), polybutyrate terephthalate

(PBT), polybutyrate succinate (PBS) and polyamide (PA) are all currently derived from petrochemical feedstocks (Patel and Crank, 2007). Both bio-based PUR and PTT do not satisfy the property of recyclable and biodegradability. Renewable feedstock constitutes only one part of the two monomers forming PTT (Patel and Crank, 2007). Starch polymer products are currently blended with petrochemical co-polymers derived from fossil feedstocks.[1]

The two materials that conform are PLA and PHA. PLA is a versatile polymer, recyclable and compostable, with high transparency, high molecular weight, easy to process and water solubility resistance (Auras *et al.*, 2006; Cabedo *et al.*, 2006; Kale *et al.*, 2006; Siracusa *et al.*, 2008). Although PHA has some highly attractive qualities for thermoprocessing applications, high production cost has inhibited this polymer from entering bulk markets. Comparatively, PLA is more transparent and tougher than PHA, and is available in larger quantities at lower price, exhibiting both technical and economically superior over PHA.

3. Supply chain process of PLA

The use of PLA is contentious in part because it is derived from corn, and competes in both land and end use with food and bio-fuels. In this section, we examine the interrelationship between the production of PLA and alternative uses of corn, including as a source of food. Polylactic acid is an aliphatic compostable polymer currently derived from corn. A simplified flow diagram of the PLA supply chain is described in Figure 1. It consists of several main components, i.e. production of corn and its competing uses, production of PLA, use of end products, recycling and waste treatment. The supply chain includes all the relevant inputs in the production of corn

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[1] Patel and Crank (2007) suggests that up to 50 % of the total mass of the starch polymer products is blended with petrochemical co-polymers.

such as corn seed, fertilizers, electricity, fuels, irrigation water, herbicides and insecticides used to grow corn.

After harvest, the corn grain is transported to a corn wet mill, while corn stover is currently ploughed back into the corn field. However, future technologies will use this byproduct from corn to produce biofuels. Apart from starch to produce PLA, the current competing uses of corn are for human food, biofuels and animal feeds. The corn grain that is milled into starch is separated from the other components of the corn kernel – protein, fats, fibres, ash and water. The starch is then saccharified into dextrose using enzymes. The other by-products are corn gluten, meal and germ. The sugar ferments and then several separation steps follow until the final product purity is achieved and extracted. The purified fermentation product is a monomer that is further processed, for example, to increase optical purity. The monomer may then be polymerized or combined with other chemicals to produce a final product with desired physical properties. The resulting polymer pellets are then moulded into the consumer product, which competes with plastics from petrochemical feedstocks in the market.

Currently, PLA is mainly used for packaging applications only for short-life products (Siracusa *et al.*, 2008). The PLA pellets are transported to package convertors, who transform these pellets into different packaging shells, which are then distributed to different manufacturers for packaging their products. Once the lifetime of the packaging material has expired (from manufacturer to retailer to customer), it is disposed of either by grinding it back to form PLA pellets, or recycled into lactic acid, with the further option of composting. Degradability of PLA is driven by hydrolysis, which needs temperatures greater than 58° C to reduce the molecular

weight. A biodegradable product releases carbon dioxide and water vapour into the air while also undergoing biological decomposition.

Currently PLA is made entirely from corn which competes with other uses, as shown in Figure 1, influencing the primary feedstock prices. The use of PLA, especially in the plastics packaging, containers and cutlery markets, is being highly promoted because of its environmentally friendly characteristics. Environmental benefits include product biodegradability, composting of waste by-products from PLA production, growth in the use of plant-based materials, which reduces carbon dioxide in the atmosphere, and the potential energy saved versus conventional polymer production.

3.1. US corn market: food versus fuel and plastics

Nowhere is the contention over the use of corn to supply industrial feedstock better illustrated than the experience of the US (Herrera, 2006). Hence, in this sub-section, we examine the US corn market for interrelationship between the production of PLA and alternative uses of corn, including food. In the following sub-section, we examine the technical aspects of PLA. The US production of corn, in general, has trended up since the 1960s, however, crop area has not increased significantly; in 2009, US farmers planted 84.98 million acres of corn with production reaching 11.93 thousand million bushels . Using data drawn from supply and usage provided by the USDA's National Agricultural Statistics (USDA, 2009), it can be seen that after 1996, there was a significant increase in yield with near constant area. However, the area under corn increased substantially for a year in 2007 and then declined, failing to respond to increasing corn prices that continued to rise since 2006. Both corn production and price show a noticeable divergence until 2004, but unexpectedly after that both production and price tend to move

together. This is unexpected as higher output puts pressure on price, unless demand is increasing much faster.

Total corn usage comprises of animal feed, human food, seed, biofuel and other industrial uses. The principal uses of corn are in animal feed and industrial use with relatively greater long term growth for feed. However, since 2004, growth in industrial use increased by an average of 9.6 percent per year, whilst feed increased by only 0.73 percent per year. Figure 5 shows that the share of ethanol in total use of corn increased from 9 percent in 2001 to 39 percent in 2009, whereas corn used for feed declined from 74 percent to 49 percent. Although supply of corn is increasing, total domestic use seems to be growing much faster, primarily for ethanol.

Global biofuel production has more than tripled from 4.8 billion gallons in 2000 to about 16.0 billion in 2007, but still accounts for less than 3 percent of the global transportation fuel supply. About 90 percent of production is concentrated in the US, Brazil and the EU. The US congress, under the 2007 National Renewable Fuel Standard program, has mandated production of 36 billion gallons of all biofuels by 2022 (USEPA, 2009). In 2007, about 49.60 percent of total world fuel ethanol production in the US with Brazil at 38.31 percent. Corn-based ethanol production in the US grew rapidly during the present decade, from 1.6 billion gallons in 2000 to 9 billion gallons in 2008 (Renewable Fuels Association, 2009). The total corn area used for ethanol production increased from 24 percent in 2007 to 29 percent in 2008, and about 8.7 million hectares of biotech corn in the year 2008 was devoted to ethanol production (James, 2008).The demand for corn increased from less than 50 percent in 2004 to more than 75 percent in 2009, doubling corn prices over this period. Although other factors like higher energy costs, tight global grain supplies, strong export demand and rapidly growing Asian economies could

perhaps indirectly play an important role. Corn-based ethanol, however, remains controversial from land-use perspective, and also from the critical standpoint of reducing overall greenhouse gas emissions (Searchinger *et al.*, 2008; Rajagopal and Zilberman, 2008).

3.2. Technical superiority: comparative properties of PLA and PET

PLA has demonstrated its value in use. It is the only commercially produced biobased polymer suitable for bulk applications; sometimes described as a 'new paradigm' in the bulk application polymer field. While sharing some properties with both synthetic thermoplastics and bio-based polymers, it conforms to certain properties that are typical of a non-polymer material (Dorgen 2003). Currently, PLA is mainly used for food packaging applications (70 percent) and fibres (3-28 percent) (Crank *et al.*, 2005). Other applications include fibres for apparel, consumer goods, etc. Food-contact articles made from PLA have been shown to be safe based on experimental data (Conn *et al.*, 1995; Auras, *et al.*, 2006). PLA compares favourably to polyethylene (PE) in terms of its aroma barrier, grease resistance, stiffness and has a higher modulus (Crank *et al.*, 2005). Since PLA is widely seen as having the potential to replace PET in certain important applications, such as fibres and packaging (Pelsoci, 2007), we restrict our comparison here to this polymer.[2]

In Table 3, we present the comparative technical properties of both PLA and PET. PLA has medium degree of polymerization which is similar to PET. The hardness, stiffness, impact

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[2] Results based on interviewing industrial experts, Shen *et al.* (2010) estimate 20% as the maximum technical potential of PLA to replace PET.

strength and elasticity of PLA, important for certain applications, such as beverage flasks, are similar to PET. Similarly both PLA and PET are not suitable for filling at elevated temperatures. Compared to PLA, PET has better printability and better barrier properties. While PLA is a poor barrier for water, a useful property for fog-free packaging, it is becoming a growing alternative as a green food packaging material, since in many situations it performs better than synthetic PET (Auras *et al.*, 2005; Crank *et al.*, 2005).

The use of PLA, especially in plastics packaging, container and cutlery markets, is being highly promoted because of its environmentally friendly characteristics. Environmental benefits include product biodegradability, composting of waste by-products from PLA production, growth in the use of plant-based materials, which reduces carbon dioxide in the atmosphere, and the potential energy saved in production (Figure 2). Unfortunately, degradation of PLA is driven only by hydrolysis at temperatures greater than 60° C (Crank *et al.*, 2005). Gross and Kalra (2002) suggests that PLA by 2020 could displace polymers worth 192 trillion BTU of fossil fuel, which is equivalent to 10 million tons of CO_2 emissions per year.

4. Economic superiority: comparative aspects of PLA and PET

The previous section demonstrated that PLA is technically superior to PET in its performance characteristic. In this section, we focus on the comparative economic aspects of the two competing technologies. In terms of production, the US continues to be the largest producer of PLA, followed by Western Europe and China. The US surpassed Western Europe as the largest producer in 2001-2002, with the commissioning of Nature Work's polylactic acid plant, which had a capacity of producing 140 thousand tonnes per year. In mid-2009, Nature Works expanded its PLA capacity in the US with an additional 70 thousand metric tonnes. The new company has

significantly reduced production costs, while expanding the use of polylactic acid beyond biomedical applications (Gruber and O'Brien, 2002). In the US, PLA demand for industrial applications, such as fibres, containers and packaging, is expected to continue to increase. Likewise, demand for PLA will increase significantly in Western Europe, mainly for packaging uses. Nature Works predicts that within the next 10 to 15 years there will be a major shift away from packaging and towards fibres and fabrics, transportation and electronics (Patel and Crank, 2007).

Table 4 summarizes the comparative economic aspects of PLA with its nearest competitor PET. The first column shows that the cost of production for PLA is much higher than PET, which is reflected in the product market price (Col. 2). While PET has a market share of 19 %, PLA market share is less than 0.1% of the total plastics sold. However, adoption, given in column 4, shows that percentage annual growth of PLA is higher at 15 percent compared to 11 percent for PET.[3] Although PLA is technically superior, at least in some applications, it is still not cost effective, but adoption is higher than for PET. This is in contrast to the fairly familiar literature on the 'energy paradox' of a very gradual diffusion of apparently cost-effective energy-conserving technology (Jaffe *et al.*, 2005).[4]

The adoption rate could be regarded as ephemeral, largely driven by regulation that induces new technology, such as Packaging and Packaging Waste Directive 94/62/EC and End-of-Life

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[3] The average annual growth rate of biobased plastics market is much higher at 40% worldwide between 2003 and 2007 and in Europe, much higher at 50% (Shen *et al.*, 2010).

[4] Often cited examples include compact fluorescent light bulbs, improved insulation and energy-efficient appliance (Norberg-bohm, 1990).

Vehicle Directive 2000/53/EC.[5] There is though more to explaining the relative lower adoption of PLA compared to PET in the long run. The first explanation hinges on questions of cost; divergence between economic and technical superiority can lead to market failure. PLA is not a new polymer rather it has been used for several decades in high-cost specialty medical products. Carothers in 1932 first pioneered the manufacture of polyester from lactic acid which was further developed by Dupont (Holten, 1971). Wider application of PLA beyond the medical field was restricted by high production cost. But with major breakthroughs in processing technology in the 1980s, the cost of production of PLA declined leading to large-scale production and wider applications (Gross and Kalra, 2002). Further reductions in cost are expected with improvements in the fermentation process and the use of waste agricultural materials as feedstocks (Ragauskas *et al.*, 2006). Despite these cost gains PLA still costs more than PET.

The second explanation of PLA adoption rate is linked to why PET has lower cost. An important reason is that the cost of producing PET excludes its environmental cost (termed negative externalities in economists jargon) If the environmental cost of producing PET or PLA were to be fully included in the material product price, the price gap between them would be much smaller. In some circumstances accounting for the full environmental cost could mean PLA becoming a more economically efficient use of scarce resource. This environmental cost is directly related to use of petroleum feedstock. The reason for the lower adoption of PLA is because of a market failure.

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[5] In 1994, Cargill received part funding from the US government under the Advanced Technology Program to develop the fundamental methodology for controlling PLA crystallinity and utilized that knowledge to develop processing technologies to achieve the resin properties required for a variety of polymer products (Pelsoci, 2007).

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The market price of polymers based on petroleum feedstock is much lower than PLA, which does not exhibit the negative environmental externalities that are innate to the product and its production methods. Figure 3 illustrates this using a simple demand-supply framework. Let D be the downward sloping total demand curve in the plastics market. Supply-side of the plastics market is segmented with Q^P_{PET} quantity of PET supplied at P^P_{PET} prices. Here price P^P_{PET} represents the private cost of production with market equilibrium denoted by a. The plastics market currently is characterized by multiple equilibrium with a segment supplied with PLA. The price of PLA denoted by P^P_{PLA} is higher than the price of PET. The market equilibrium for PLA is denoted by b. However, the social cost of production of PET is much higher than the cost that is reflected in the market due to externalities created in the production of PET (Figure 2). The social costs, when internalized, increase the price of PET to P^S_{PET}, as shown in Figure 3. This is higher than the cost of production of PLA as emissions from PET are much higher (Figure 2). Currently, the market price of PET does not reflect the full economic resource cost, including environmental cost. While more expensive, PLA are environmentally benign. The market failure to properly reflect hidden economic and social costs in the market price of petroleum feedstock is likely to also increase the switching costs of PLA. Such market failures can create divergence between technical and economic superiority, hindering further diffusion of PLA in the long run.

Currently the costs of switching between processes with different feedstocks are high. The consequence is the current processes of production of cheaper plastics are locked-in into a particular feedstock, namely oil. It is the processing cost of biomass raw material that is not cost effective, while the raw material itself costs less than the cost of petroleum on a cost per kilogram basis. There is a huge raw material cost advantage for the biobased products industry.

The cost of the transformation process that implicitly embodies different technology is higher under PLA compared to oil-based. Nevertheless, the market price of the PLA is more likely to fall due to dynamic efficiencies gained in the long-run from learning-by-using, learning-by-doing and scale economies with greater production.

4.1. Energy price increase and adoption of PLA

Several recent studies suggest that higher petroleum prices beyond the critical threshold will make bio-materials a cheaper alternative (Lorenz and Zinke, 2005; Cassman and Liska, 2007).[6] However, this may not necessarily be true, especially for PLA, because several agricultural processes in the production of corn – the main input into PLA production – are not only energy intensive but also have high price elasticity. In this section, we examine in detail if higher energy prices can make PLA more cost effective.

The impact of energy price increase on the production of corn can be demonstrated as follows: Consider the following production function for corn with capital denoted as K, labour as L and energy as E.

$$Q_C = f(K, L, E) \tag{1}$$

where Q_C is gross output. Let the net output denoted by Y_C be

$$Y_C = Q_C - P_E E \tag{2}$$

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[6] For instance, Cassman and Liska (2007) point out that at prices above US $50 per barrel, it is profitable to produce ethanol from maize grain without subsidies.

where P_E is the relative price of energy and the price of output is the numeraire. Substituting (1)

into (2) and setting the marginal product of each factor input equal to its price, the effect of a

change in the price of energy on net output of corn is given as

$$\frac{d \ln Y_c}{d \ln P_E} = \left[\frac{P_K K}{Y_c}\right] \frac{d \ln K}{d \ln P_E} + \left[\frac{P_L L}{Y_c}\right] \frac{d \ln L}{d \ln P_E} - \left[\frac{P_E E}{Y_c}\right] \quad (3)$$

Here P_k and P_L are the relative prices of capital and labour, respectively. The effect of change in

the price of energy depends on the cost share of energy in total output and the substitution

possibility between energy and both capital and labour. Equation (3) has three components with

the last showing a negative direct effect that depends on the amount of additional resources

required. The impact of the first and second components is generally positive in an economy

where substitution possibilities away from energy are high. But the large size of US corn farms

limits the simple possibility of substitution between energy and both labour and capital. Energy

prices affect corn production costs directly through fuel and energy use, and indirectly through

the use of farm inputs such as fertilizer and chemicals that are closely related to fossil oil prices.

The short run demands for direct and indirect energy inputs in the US agriculture are price

inelastic (Miranowski, 2005). Figure 4 shows that both direct and indirect expenditure on energy

inputs in the US between 1945 and 2005, which now constitutes about 23 percent of all

purchased inputs, have closely moved with fuel and energy prices changes.

Higher fossil fuel prices, such as those experienced in recent years, also put upward pressure on

the costs of corn production (Elobeid and Hart, 2007). Since corn is an important feedstock in the

production of PLA, we expect that higher corn prices will have some effect on the price of PLA.

This upward pressure on the prices of PLA, although indirectly due to increase in the price of

fossil fuel, will further erode the cost competitive advantage rather than making PLA more competitive.

Higher energy prices provide incentives for policies that strive for energy independence and continued support for subsidies and tax credits to support ethanol production. Since corn is the primary grain used for ethanol production in the US, the increased demand for corn is expected to put an upward pressure on corn prices. This being the primary feedstock in the production of PLA, the cost of production of PLA will increase. Moreover, higher oil prices also result in higher fuel and energy costs, which also increase the production costs of PLA. Whether PLA becomes cost effective as fossil prices increase, therefore, depends on relative increases in the prices of PLA and fossil based plastics, and whether the bio-plastics industry is able to pass on the higher costs. In other words, industry structure and relative supply and demand elasticities have a significant effect on the degree to which PLA suppliers can pass higher costs onto package converters and finally, to consumers. This however is an empirical question that is beyond of the scope of this paper, but will be explored in our future research.

5. Potential solutions to make PLA cost effective

The previous section showed that any increase in the price of fossil fuel is likely to induce inflation leading to higher production cost of PLA. So if higher energy prices are unlikely to provide an incentive to make PLA cost effective, the question remains as to what other options exist to promote its uptake. In this section, we examine this question looking at future technological development and market expansion. The cost effectiveness aspect of PLA might have to focus on the technology advancement (production from lignocelluloses, cheaper

innovative process) and marketing (projecting the green technology) for adoption and diffusion to be higher than fossil fuel based plastics.

While grain might be used to produce chemicals and plastics with little or no effect on food supplies, there is not sufficient grain at low enough prices to replace all but a relatively small percentage of liquid transportation fuels. However, there is ample lignocellulosic biomass material (grasses, hays, crop residues, trees, etc) to supply large quantities of liquid transportation fuels if effective, economical conversion technologies can be developed. One of these enabling technologies that have yet to be developed is a low cost, high yield pretreatment to efficiently and economically increase the yield of fermentable sugars from treated lignocellulosic biomass. If such pretreatments are developed, the vast reservoir of sugars in lignocelluloses will also become available for animal feeding, likely relieving any pressure on feed/food supplies (Dale, 2003).

Another fascinating possibility, one which has no counterpart in petroleum refining, is to alter the composition of the plant material, either by traditional breeding or molecular biology. The ability to modify the raw material of the conversion process is a major potential advantage of biobased products compared with petroleum-derived products. This advantage should be exploited at every opportunity. Altering the composition of the plant raw material may significantly increase the ease (and thereby reduce the cost and environmental impact) by which the plant is processed to the desired final products. Genetic engineering may also provide the means of introducing valuable new products into the plant raw material (e.g. valuable proteins, carbohydrates and lipids), thereby increasing the returns to the farmer and the overall economic viability of biobased products.

The long term growth of PLA will depend on the development of cost-competitive technology and access to diverse markets. The adoption of PLA will require change in the capacity of the chemical industries involving huge capital costs to switch from crude oil to biomass. The final cost of producing PLA depends primarily on the efficiency of the initial fermentation process to produce the lactic acid monomer (Petersen *et al.*, 1999). Lactic acid currently comprises around 40 to 50 percent of NatureWorks total costs. With large scale production and learning through practice cost is likely to decline further.

Apart from supply, demand factors also can play an important role with PLA facing entry barriers from existing complimentary technologies (Reingabum, 1981; Quirmbach, 1986). Hence, market expansion of PLA is likely to see some resistance from the suppliers of substitute resins (such as PET), and also from current package converters due to locked-in capital in established resins. Overcoming these barriers is important for adoption to be maintained at the current rate.

6. Conclusion

PLA although energy efficient is still not as cost effective as alternatives, however, it is being adopted at a rate that is higher than conventional plastics. This is most likely driven by disincentives created by end-use packaging legislations and also short-term concerns for the environment. The food and beverages market with its growing demand for packaging applications is likely to further boost the market for PLA. Two important log-term concerns that were highlighted are divergence between technical and economic superiority and market failure. Thus the main drivers of adoption in the long-run are expected to be declining production cost,

environmental legislation concerning waste disposal and composting, and consumer attitudes towards environmental impact.

Given competing uses of corn and a growing demand for ethanol production, corn prices are likely to see an increase, largely driven by biofuel policies striving to reduce the use of fossil fuel. Since this will have a direct impact on the cost-effectiveness of PLA, policies should either reduce subsidies to biofuel or also extend this subsidy to PLA as well. Lastly, we show that higher petroleum prices, beyond a threshold after which PLA becomes cost effective, is not a viable option because higher petroleum prices also increase the cost of production of PLA. Biotechnology to modify plant raw materials, such as crop residues, has potential to make PLA production more cost effective, but raises the question as to whether a bio-plastic based upon genetically modified technology is acceptable as a 'green' alternative by consumers and environmental NGOs, which may act as a barrier to adoption.

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Table 1: Sustainable material technology (SMT) matrix

		Renewable	Nonrenewable
Reuse		SMT	
Recyclable	Biodegradable	SMT	
	Non-biodegradable	SMT	
Non-recyclable	Biodegradable		
	Non-biodegradable		

Table 3: Technical superiority: comparative properties of PLA and PET

| Properties	PLA	PET
Chemical	medium degree of polymerisation	similar to PLA
Physical	lower gravity	higher gravity
Mechanical	low impact strength	similar to PLA
Thermal	degradable, reasonable heat resistance	non degradable, better heat resistance
Other	poor barrier of water	Better barrier

Source: Crank, M., Patel, M., Marscheider-Weidemann, F., Schleich, J., Husing, B. and Angerer, G. (2005)

Table 4: Economic superiority: comparative economic aspects of PLA and PET

	Cost of production (US$/lbs)	Price (US$/lbs)	Market share (% of total plastics)	Adoption (% annual growth)
PLA	3.39*	3.50*	<0.1**	15****
PET	0.15***	0.5***	19***	11***

Source:* Wee, Kim and Ryu (2006); ** Own estimate; ***European Plastics Converters (2007): **** Pelsoci (2007)

Figure 2: Fossil energy use for PLA and PET
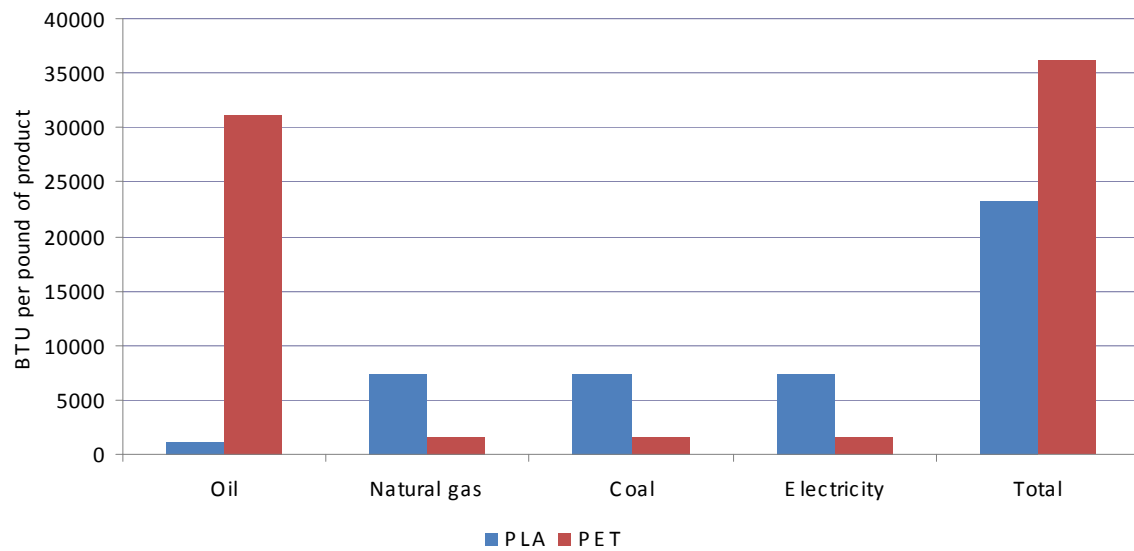
Source: Vink, Rabago, Glassner and Gruber (2003).

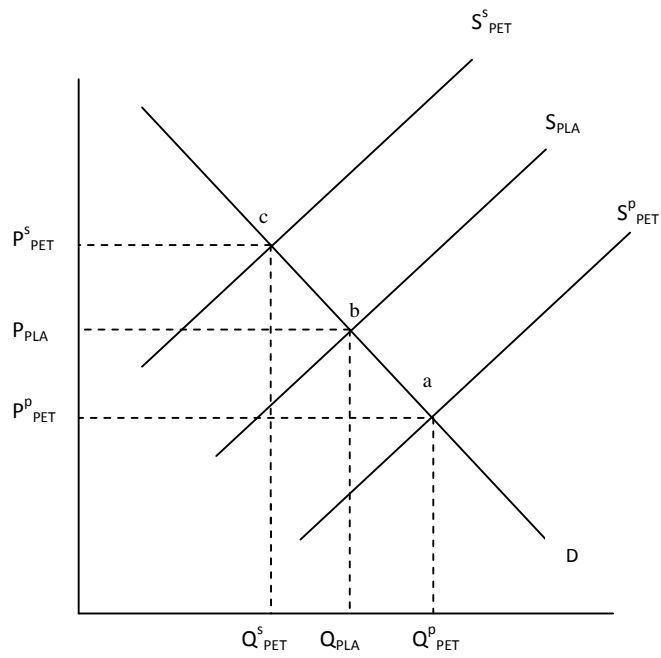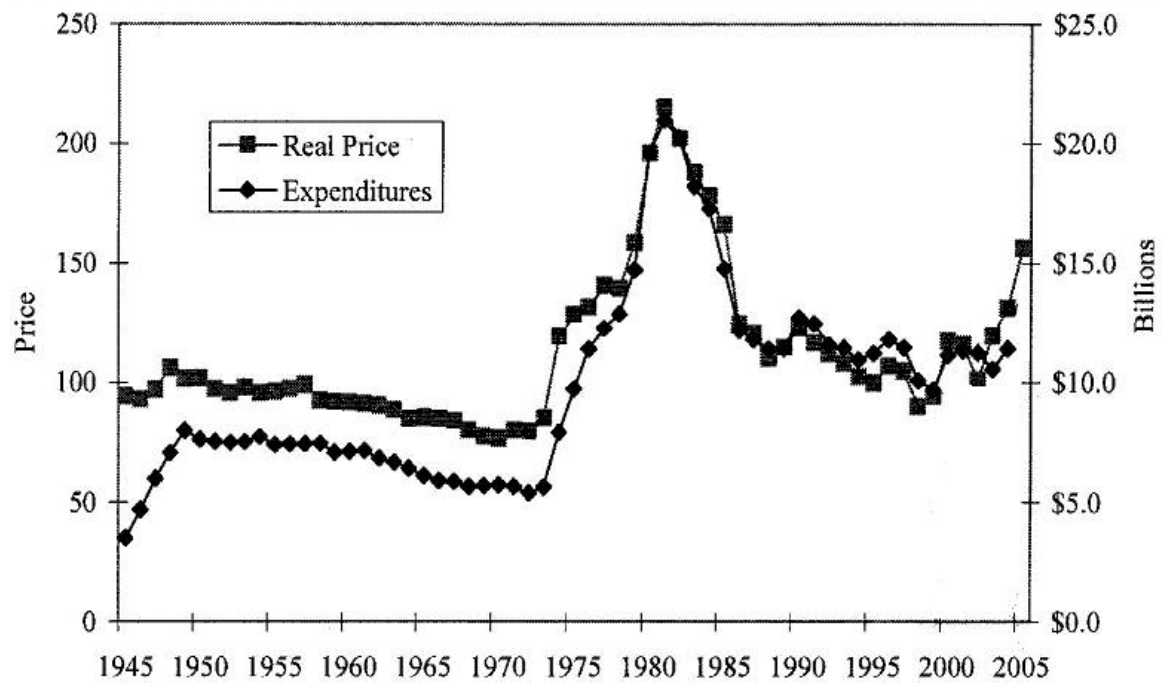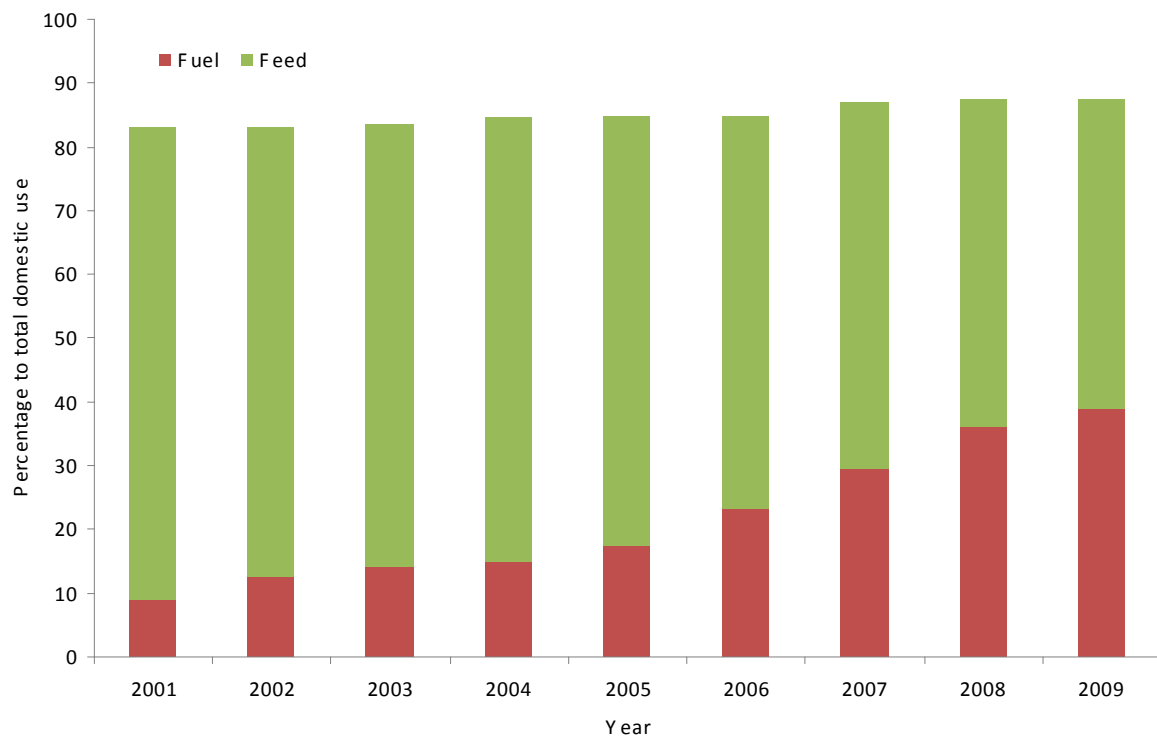Figure 3: Market failure in the plastics market

Figure 4: Energy price and total agricultural expenditure on energy inputs in the U.S.

Source: Lambert (2006)

Figure 5: Domestic demand for corn

Source: USDA (2009)
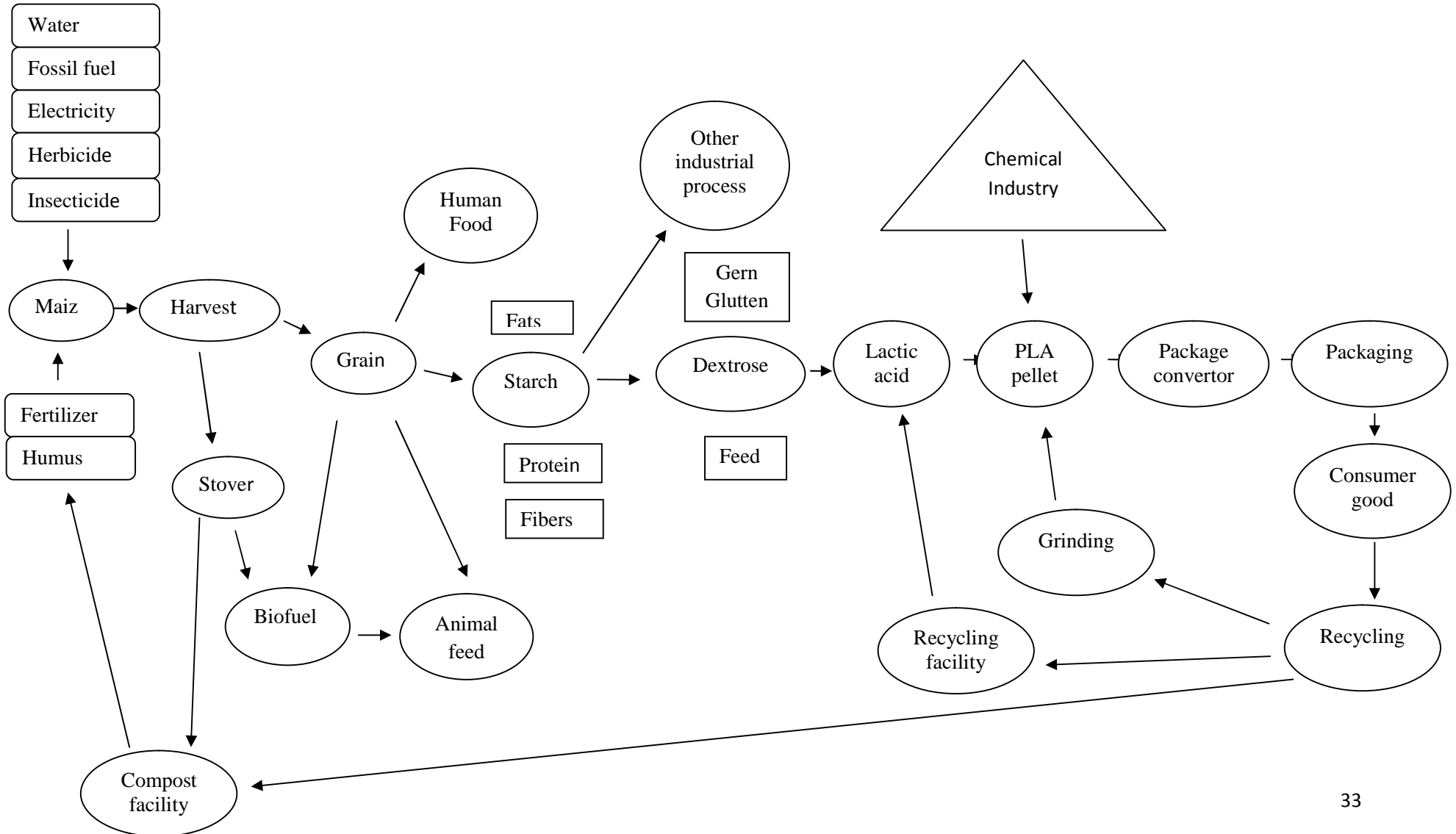
Figure 1: PLA Supply Chain

Table 2: List of different polymers using biomass feedstock

Materials	Design	Manufacture							Disposal		
	Reduce	Reuse	RE	NRE	RC		NRC		Compost	Incineration	Landfill
					BD	NBD	BD	NBD			
Polylactic acid (PLA)	X	X	X		X				X		
Polyhydroxyalkanoates (PHA)			X		X						
Polytrimethyleneterephthalate (PTT)				X				X			X
Polybutyleneterephthalate (PBT)				X							X
Polybutylene succinate (PBS)				X	X						
Polyurethanes (PUR)				X				X			X
Polyvinylalcohol (PVOH)	X			X			X			X	
Polyamide (PA)				X							
Polycaprolactone (PCL)				X	X						
Polysaccharides (Starch)	X			X			X			X	
Propanediol (PDO)			X	X	X						

Notes: (a) RE refers to renewable; NRE refers to non-renewable; RC refers to recyclable; NRC refers to non-recyclable; BD refers to biodegradable; NDB refers to non-biodegradable

(b) 'X' refers to the respective characteristic being satisfied by the material.