OPPORTUNITIES FOR BIO-POLYMER RESOURCE CONSERVATION THROUGH CLOSED LOOP RECYCLING

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Abstract

Oil-derived plastics have become well established as a packaging material over the past 75 years due to their many technical and commercial advantages. However, the disposal of plastic packaging waste, a large proportion of which still goes to landfill, continues to raise increasing environmental concerns. Meanwhile, the price of oil continues to rise as demand outstrips supply. In response, biodegradable polymers made from renewable resources have risen to greater prominence, with a variety of materials currently being developed from plant starch, cellulose, sugars and proteins.

Whilst the polymer science continues apace, the real ecological impacts and benefits of these materials remain uncertain. Although life cycle assessment (LCA) has been used to provide comparisons with oil-derived plastics, published studies are often limited in scope, allowing the validity of their conclusions to be challenged. The literature appears to support the popular assumption that the end-of-life management of these materials requires little consideration, since their biodegradable properties provide inherent ecological benefits. Opportunities for conserving resources through the recycling of biopolymers are rarely addressed.

Through a review of current academic, industrial and commercial progress in the field of biopolymers, a number of LCA case studies are proposed which will address this weakness in existing research, related to the recycling of biopolymers. These, or similar, studies are required to provide a more complete picture of the potential effects of a transition from non-renewable to renewable polymers, thus allowing material selection decisions to be made with greater confidence throughout the packaging supply chain.

Introduction

The annual global production capacity of bio-derived polymers, based on company announcements, is forecast to grow from 0.36 Mt (million metric tonnes) in 2007 to 2.33 Mt in 2013, an annual increase of 37 percent. (Shen et al., 2009). In addition, the types of products and brands using bio-derived polymers (BDPs) for their packaging has begun to shift from predominantly niche, unprocessed items such as organic fruit and vegetables, to more mainstream global consumer brands such as cola, crisps and chocolate. The rate and scale of this change has been highlighted through a study of company, press and trade announcements on new products launched in BDP based packaging. The results of this study were then analysed in terms of the number of announcements per year and the general significance of each with regard to the importance of the brand, the size of the company and market and the level of technical performance.

Although there are many factors which have influenced the growth and development of BDPs, the most fundamental of these has been the growing public desire for environmentally friendly and sustainable packaging, and the popularly held belief that bio-derived polymers meet this requirement. To a large degree this view has been fostered both from the claims made by manufacturers, and the obvious emotional attraction towards a material with a natural, renewable pedigree. However, the factors now influencing the adoption of bio-derived polymer have shifted from niche catagory, market driven demand to mainstream political policy, with numerous government initiatives actively promoting and encouraging the procurement of 'bio-based' and 'sustainable' products.

Whilst well intentioned, the current level of scientific understanding of the environmental benefits achievable from these materials, particularly for certain packaging applications and end of life scenarios, is inadequate or simply non existent. The danger in creating an artificial market for these materials, whilst questions remain about their overall benefits, is that it may force the premature adoption of a particular technology or material, which in turn could hinder the development of more effective and sustainable environmental solutions in the future. It also increases the risk of a consumer backlash if these premature claims are then proven to be false or vacuous.

This paper begins with an overview of the major conventional and bio-derived polymers used in packaging applications, comparing the key types of packaging application and end of life management options. Next the findings from a study on the reported packaging applications of bio-derived polymers for new product launches from 2004 to 2009 are discussed, followed by a review of the major drivers and barriers that have influenced their growth both negatively and positively. The results of a literature review on published LCA studies for both bio-derived and conventional polymers are then discussed. The paper concludes by highlighting the key challenges that must be met to enable the long term sustainable adoption of bio-derived polymers as a mainstream packaging material.

Polymers in Packaging Overview

Packaging uses approximately 37% of the 260 million tones of plastics produced globally each year, (Plastics Europe, 2008), which equates to just over 1% of the world's total crude oil production, the majority of which being 'burnt' as fuel for power generation or transport, (Queiroz & Collares-Queiroz, 2009). However, plastics packaging is highly visible and pervasive, and as a result has become almost symbolic of our modern society's excesses and wastefulness. The reality however is more complex, food waste from farm/factory to shop in Western Europe is 2-3%, compared with 30-50% in developing countries (Incpen, 2009). So it is more often the case, that when used correctly, plastics packaging can actually save energy, being lightweight, rugged, versatile, safe and capable of meeting a range of mixed barrier requirements for longer shelf life and less product waste.

It is however this combination of plastics' durability and packaging's disposability that attracts so much negative press, and has contributed to packaging becoming the first industry to be targeted by specific waste legislation, arising from the EU's Directive 94/62/EC on Packaging and Packaging Waste. Despite the many regulations and initiatives to limit the use of plastics packaging, consumption has continued to grow at an average of 9% annually (Plastics Europe, 2008).

The majority of polymers used in packaging are thermoplastics, this means they can be re-heated and re-formed multiple times, making them suitable for recycling provided they can be separated into their specific polymer types. The most important of these are PE, PP, PVC, PET and PS, which account for 96% by dry weight of polymers used for packaging applications, of which over 70% are used for food and beverage packaging, as shown in Fig 1 (Applied Market Information, 2008)

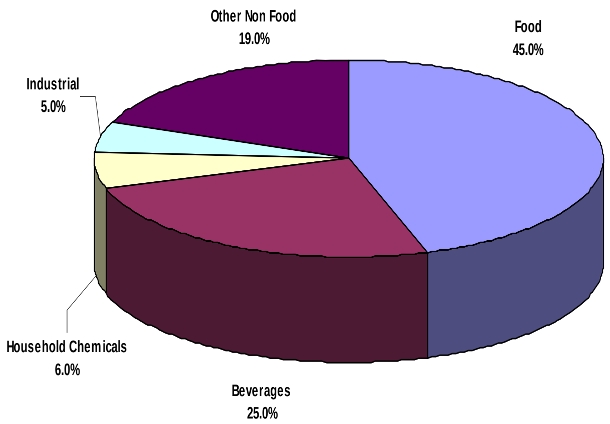

Figure 1 End Use applications for polymer packaging in Europe 2007 – Source data: Applied Market Information

Bio-derived polymers, which have developed both technically and commercially over the past 20 years, are now appearing in mainstream packaging applications. Two distinct routes have begun to emerge; those materials which largely retain the original source material's properties, namely their ability to bio-degrade and / or be compostable, which we will refer to as 'Class A' bio-derived polymers (BDPa), and those that are identical to the current fossil derived polymers, such as PE, PET, PVC, but are produced from a bio-derived intermediate such as bio ethylene. These we will refer to as 'Class B' bio-derived polymers (BDPb). The key fossil-derived (FD) and bio-derived (BD) polymers and their main packaging applications are shown in Table 2.

Key
w wholly applicable
p partially applicable
\- unknown

*BE – produced from bio ethylene

			Packaging Applications				End-of-Life Management			
			Flexibles – films, bags…	Semi Rigid – ThF, SBM - Trays, bottles…	Rigid – Inj. Moulded - caps, devices…	Foamed – Moulded, extruded – Filler, pads…	Compostable - Home	Compostable - Commercial	Bio-degradable	Recyclable
Fossil Derived – Conventional Polymers	**PE**	**Polyethylene**	W	W	W	W				W
	LDPE	Low Density PE	W			P				W
	LLDPE	Linear Low Density PE	W							W
	HDPE	High Density PE	W	W	W	W				W
	PP	**Polypropylene**	W	W	W	W				W
	OPP	Orientated PP	W							W
	BOPP	Biaxially Orientated PP	W							W
	PS	Polystyrene	W	W	W	W				W
	PET	**Polyethylene Terephthalate**	W	W						W
	APET	Amorphous PET	W	W						W
	PETg	PET Glycol		W						W
	CPET	Crystallised PET	W	W	W					W
	OPET	Orientated PET	W							W
	PVC	Polyvinyl Chloride	W	W	W					W
	PA	Polyamide - Nylon	W	P	P					W
	PVA	Polyvinyl Alcohol	W	P			P	P	P	-
Mixed	PVC	Polyvinyl Chloride – BE*	W	W	W					W
	PET	Polyethylene Terephthalate – BE*	W	W						W
	Blends	Starch blends (FD copolymers)	W	W	P	W	P	P	P	
	Blends	PLA blends (FD copolymers)	W	W	P		P	P	P	
	Blends	Conventional FD/BD blends	W	W	P			P	P	
Fully Bio-derived	RC	Regenerated Cellulose	W				P	W	W	W
	CA	Cellulose Acetate	W				P	W	W	W
	PE	Polyethylene – BE	W	W	W	W				W
	PP	Polyproylene – BE	W	W	W	W				W
	TPS	Thermoplastic starch	W	W	P	W	P	W	W	W
	SA	Starch Acetate	W				P	W	W	W
	PLA	Polylactide - Poly Lactic Acid	W	W	W		P	W	W	W
	PHA	Polyhydroxyalkanoates	W	W	W		p	W	W	W

Table 1 – Key packaging polymers and their application and end use characteristics

Applications of Bio-derived polymers

Bio-derived polymers have been used as packaging materials since the 1950s with the development of cellulose film, but were soon supplanted by the 'new' range of fossil derived plastics. However in the 1990s a new wave of bio-polymers emerged, driven by the need for more sustainable and environmentally friendly packaging. The first polymers were made from starch, cellulose and natural oils such as linseed, the technology for which was well known. These were followed by 'second generation' bio-polymers; PLAs, PHAs and PHBs, which could be formed. sealed or moulded using existing packaging equipment. These found application in bottles, trays and clamshell packaging. but were limited by their functional performance and barrier properties. The third and latest generation of bio-polymers to enter the market includes the 'Class B' thermoplastic polymers; PET, PE and PVC. As these polymers are identical to their FD polymer equivalents, they can be mixed together in any proportion with no noticeable difference , enabling the percentages to be adjusted as and when supply and cost demanded. They can also be recycled, mixed with their FD equivalents, with no adverse effects on the reprocessing of or the subsequent re-use of the recyclet.

To understand how the application of bio-derived polymers for packaging has evolved, an online review of published announcements for new product launches in bio-derived packaging was undertaken. This included searching the websites and press archives of all the main biopolymer manufacturers, associated trade press and the key industry bodies, associations and institutes for the environment, packaging and plastics industries, dating back to 2004. It is an expected and an accepted limitation of this review that as a material becomes established, i.e. first generation bio-polymers such as cellulose film and foamed starch chips, they will probably become less noteworthy of comment and so frequency will decline even if use actually increases. Also, the results record launch activity, not ongoing use, and so should not be viewed accumulatively.

From Table 2, we can see that food and drink account for the majority of new pack introductions whilst flexible films and bags are the dominant pack type.

Product Group		Bio-derived Polymers - Materials					Pack Types			
	Grp Total	Cell-ulose	TPS starch	PLA	PHA	BDE PET	Films /Bags	Semi-rigid	Rigid	Foam
Food	**55**	24	6	25	0	0	38	16	1	0
Drink	**12**	2	0	8	0	2	2	0	10	0
Cosmetics	**4**	1	0	2	1	0	1	0	3	0
Distributn	**2**	0	1	1	0	0	1	0	0	1
Other	**13**	1	6	6	0	0	11	2	0	0
Total	**86**	**28**	**13**	**42**	**1**	**2**	**53**	**18**	**14**	**1**

Table 2 –Product launches by BDP and pack type

This reflects the current use of FD polymers as shown previously in Figure1 and the compatibility of use with food, both in terms of origin and end of life management.

When these new introductions are plotted against their launch dates, the lower graph line in Figure 2, a picture begins to emerge of gradual annual growth in application. However, this only shows the frequency of product launches and does not consider the individual significance of each new introduction in terms of the BDP used. As it is not possible from these announcements alone to ascertain accurate data with regard to the volume of sales, material use, specific barrier properties, transmission rates etc, a simple weighting factor was applied instead. The factor used was allocated based on five easily assessable key criteria: Brand awareness, Company size, Launch market size, Potential market size and Application complexity. A weighting factor was applied for the first four criteria of 1x for local, 3x for national or 5x for global. For the fifth criteria, application complexity, a weighting of 1x for low complexity, 3x for medium (thermoformed/laminated), 5x for high complexity (injection moulded, blown, high barrier). Once applied the sum total was divided by five to a final value of between 1 and 5 for each application.

When this data is re-plotted with the weighting factor it shows a much sharper growth curve (figure 2, top line) particularly during the last two years, that might indicate that BDP's are entering a new accelerated growth phase. This would lead to higher growth than other data has previously suggested, such as BDP production capacity investments, (Shen et al, 2009) which predicts growth by 2020 to reach 3.5 Mt capacity and earlier projections published by Crank et al. (2005) of between 2.5mt and 4.17Mt. In addition, when the two graphs are compared it suggests that in addition to a general increase in use, these new bio-derived polymers are gaining wider market acceptance, moving from niche, synergetic applications such as organic, fair-trade and health food products to mainstream, high profile brands.

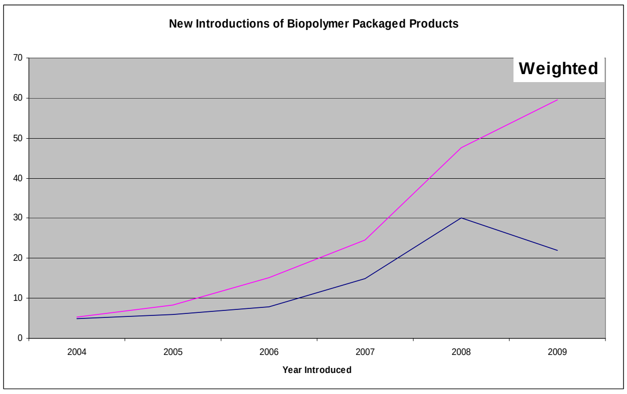

Figure 2.– Growth in BDP Applications (weighted and un-weighted) 2009 based on six months recorded data, doubled for full year

Drivers and Barriers (Limiters)

There are a number of factors which to a greater or lesser degree have had or will continue to have an influence on the development, uptake and growth of bio-derived polymers within the packaging sector. A logical division would be to separate those exerting a positive influence from those exerting a negative one, however it is possible for one factor, such as bio-fuel development, to have the potential to do both, in that it competes for natural resources but also provides a larger, more stable market allowing longer term investment and development to improve efficiencies and reduce costs. As can be seen from Fig. 3, there are numerous influences at play with direct and indirect influences and interrelations. The most important of these are listed in Table 3.

In the initial stages of bio-polymer development, market drivers such as consumer demand, oil prices and long term security of supply appeared to be the most influential. More recently policy and government initiatives including legislation such as the EU packaging waste directive EU 94/62/EC, and initiatives such as the EU's Lead Market Initiative (LMI) "Accelerating the development of the Market for Bio-based Products in Europe", the ADEME's "Bio-products Guidbook for Greener Procurements" and the USA's "Federal Bio-based Products Preferred Procurement Program" have the power to become the major influencers in BDP growth and uptake.

	Primary	Secondary
+ Positive	**The limited availability and increasing cost of fossil resources (oil and gas) and the need to secure National energy supplies.** **Policy and legislation, particularly within the area of man made climate change, sustainability and economics.** **Consumer demand driven by the growing awareness of the need for sustainable management of earths resources.**	**Organic & 'green' brands** looking for packaging that supports their corporate and brand values. **Retailer pressure** and initiatives such as the Wall-mart scorecard system and single use carrier bag reduction initiatives **Pollution** from plastic litter that does not breakdown in the environment and leads to the suffering and death of both land and marine life. **Increasing environmental damage** caused by the extraction of oil from harder to reach and more environmentally sensitive reserves such as deep sea, oil sands, polar regions etc.
- Negative	**Higher costs and more complex supply chains including capacity limitations and restricted supplier base.** **Technical performance limitations compared to fossil derived polymers in manufacturing, application and use** **Lack of clarity and quality of data regarding their overall environmental benefits. Requires detailed and independent LCA of whole process including a wider range of impacts.**	**Recycling** and the contamination of existing plastic waste streams. Not an issue with 3rd generation class b polymers produced from bio-ethylene etc. **Land availability** and competing demands of food production, energy production and preservation of natural habitats. Land is also a finite resource.
Both -+	**Bio-Fuel Development** – Competes for resources but also provides volume, secure market, and commercial scale. **Pressure Groups** – Opinion polarised between opposing fractions – Environmentalists v Business as Usual (BAU)	**New technologies** such as GM Foods (Genetic Modification) and Nano-composites. Obvious benefits in terms of performance and production efficiency improvements but concerns about their safety could lead to consumers rejection, particularly by the early adopters of these environmental products.

Table 3 Key factors influencing growth of BDP packaging

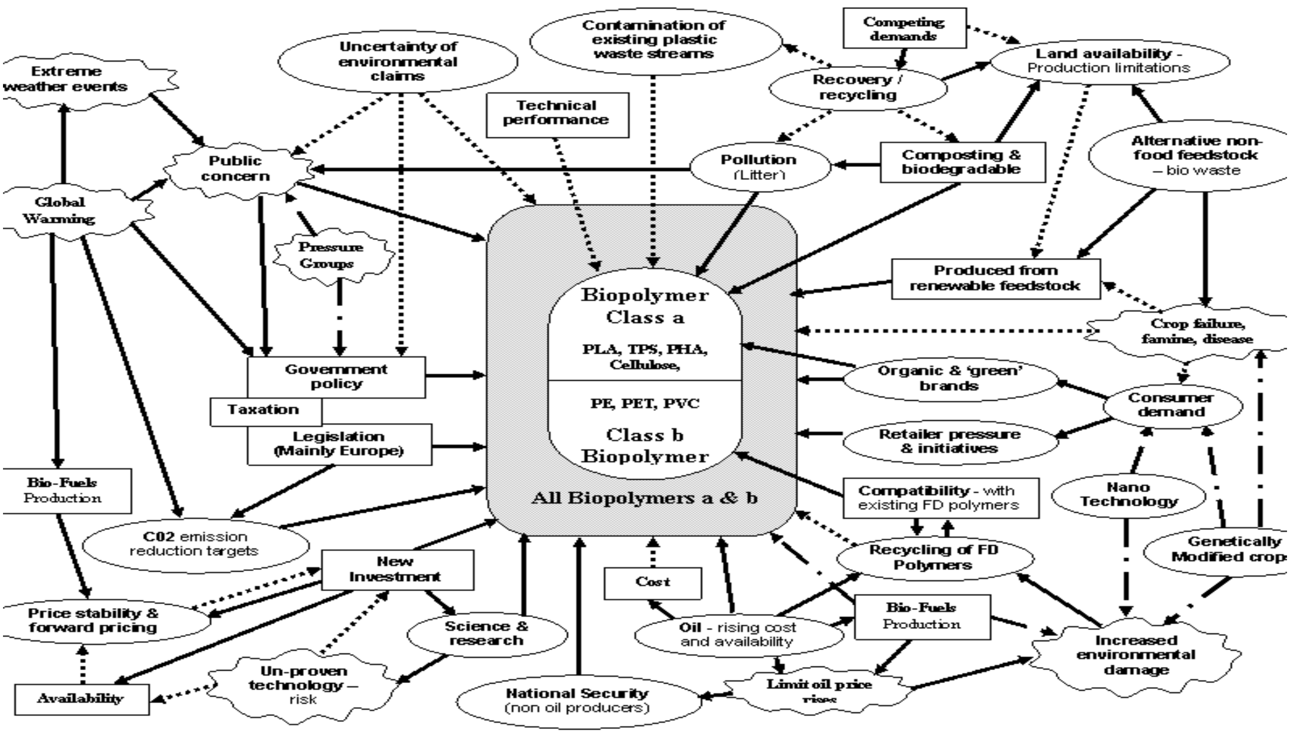

Figure 3 – Map of social, environmental, economic and political influences on Bio-derived polymer packaging

Knowledge Gaps and LCA review

Life cycle assessment (LCA) is a well-established methodology commonly used to quantitatively evaluate the environmental impacts of products and processes (ISO 2007). The method has been applied to the evaluation of BDPs for the purpose of producing environmental product declarations for commercial use, and in academic studies. Despite the development of a standard methodology for applying the LCA method, a large degree of subjectivity remains, with results often highly dependent on the definition of the system scope and boundaries.

In order to develop an understanding of the reasons for these contradictions, a systematic review of publicly available LCA reports from the academic and commercial literature was conducted, spanning a time period between 1997 and 2009. Twenty-five studies were identified and were reviewed in terms of various criteria, including the following:

- Scope of the study (life cycle stages) – which life cycle stages were included?
- Scope of the study (data quality) – how reliable was the data used?
- Scope of the study (environmental impact categories) – which environmental impact categories were evaluated?
- Independence of the study – was the study conducted or sponsored by a BDP producer?

The results from this review are summarised in Figure 5.

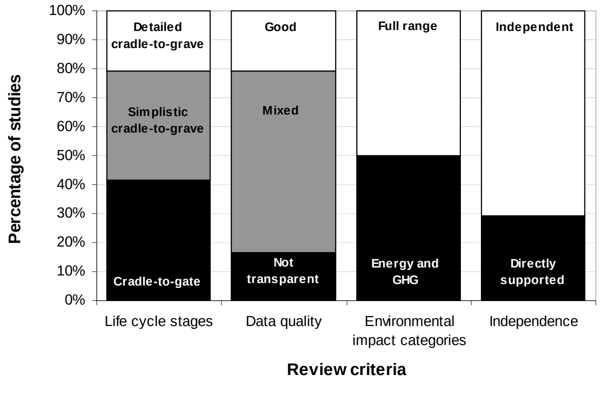

Figure 4 Review of LCA studies against review criteria 2009

production of BDPs. These cradle-to-gate studies were in general performed by BDP producers (e.g. Kurdikar *et al* 2001; Vink *et al* 2003; Vink *et al* 2007; Novamont 2009) and based on data from industrial processes. The publication of cradle-to-grave studies in which all life cycle stages were considered in any detail was scarce.

More often, cradle-to-grave studies built upon existing cradle-to-gate studies by making simplistic assumptions regarding the application and end-of-life management of BDPs and BDP products (e.g. Johansson 2005; Harding *et al* 2007; Madival *et al* 2009). The use of simple assumptions in generating scenarios for cradle-to-grave analysis is valuable in providing an indication of environmental life cycle impacts in the absence of real data. However, results from such studies must be treated with caution, and may be readily misconstrued by a non-expert reader.

The quality of data was identified as being good in situations where primary data sources, such as BDP producers, had been used. While a small number of studies were not transparent in their data sources, the majority relied on a mixture of primary and secondary data. The application of allocation rules, especially with regard to greenhouse gas and energy accounting, was identified as a cause for concern. In particular, the incorporation of Renewable Energy Credits (Vink *et al* 2007), and discounting for the use of biomass power generation systems in production facilities could bias results. Despite a high degree of transparency in the use of such allocation methods, again the concern is that a non-expert reader could misunderstand the implications of such technical aspects of LCA methodology.

It was interesting to note that around half of the studies identified focussed only on the quantification of environmental impacts associated with energy consumption and greenhouse gas production. While this reflects the current political agenda, more comprehensive studies showed that other impact categories, such as eutrophication potential, are also important in the production of BDPs (Harding *et al* 2007) and should not be ignored.

Finally, it was interesting to note that although around one third of the studies identified could be directly linked to parties with commercial interests in the promotion of BDPs, the majority of LCA studies in the published literature appeared to be conducted by independent parties. This is reassuring, since it demonstrates an appropriate level of scrutiny is being applied to the evaluation of these new materials, especially important where a methodology with tendencies to subjectivity, such as LCA, is concerned.

Concluding Discussions

Bio-derived polymers have developed and grown dramatically in the past six years, both technically and commercially, however much of the scientific knowledge underpinning this growth is fragmented and somewhat controversial. From our study we believe that BDP use is about to enter a new phase of rapid growth. The rationale for this is based firstly on the increasing influence of the three key drivers to BDP growth identified in this report (Table 3) and other published works, such as the recent Pro-Bip report (Shen et al, 2009) and the lead market task force report on bio based products in Europe (COM(2007) 860 final). Secondly, with particularly relevance to 'Class B' BDPs, from the reduction /

removal of two of the key barriers to growth. The third barrier being the need for clarity through LCA etc on the exact environmental benefits of BDPs.

In terms of the three key drivers: firstly, the number and influence of 'artificial' drivers, such as government policy, legislation and environmental taxes and levies has been increasing rapidly. Secondly 'natural drivers' such as consumer demand are likely to grow driven by a significant growth in marketing and reporting of environmental issues, in particular global warming and climate change. Thirdly, future increases in oil and gas prices are likely to reach new highs when demand returns to the global markets as economies emerge from recession.

In terms of the three key barriers identified: Technical performance and end of life issues are not relevant to the new and growing Class B BDPs. These bio-ethylene derived polymers such as PE, PET and PVC are identical to their FD counterparts. Secondly, cost and availability, one of the biggest issues for mainstream use, has to a degree been circumvented by these Class B – BDPs as they are able to be mixed with FDPs in any quantity so allowing the impact of cost and supply to be managed (A leading global soft drinks manufacturer is proposing to use up to 30% of BD PET in bottles for some of their products). Cost and supply of these Class B polymers is also being helped by the major increase in bio-fuel development. Significant investment has been made into developing large scale bio-ethylene plants to meet the EU and US targets of 10% bio fuel by 2020. This has provided a large and guaranteed market for the production of ethylene, from which the BDPbs can benefit, using this to provide economy of scale and reliability of supply.

However, all this is taking place without solid and uncontroversial scientific data in place to direct and underpin the decisions and choices that are being made.

There is a need for further and urgent LCA studies, particularly in the area of BDP application and 'end of life' management to clarify their real environmental benefits and to identify the most suitable immediate applications for their use. In addition, comparisons should be made between materials (Class A and Class B) to determine which provide the greatest benefits longer term and what are the main technical, commercial and social challenges that must be overcome, to create a long term and sustainable packaging market for these materials. It is intended that these findings will then support the future development, selection and implementation of bio-derived polymers in those areas of packaging application which deliver the greatest environmental, sustainable and ecological return.

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