Bioplastics: Assessing their environmental effects, barriers & opportunities

Valpak Consulting Consortium

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Glossary

AD	Anaerobic digestion
Biodegradability	The breakdown of an organic chemical compound by micro-organisms in the presence of oxygen to carbon dioxide, water and mineral salts of any other elements present (mineralization) and new biomass or in the absence of oxygen to carbon dioxide, methane, mineral salts and new biomass (from EN13432)
Biodegradable plastic	A degradable plastic in which the degradation results from the action of naturally occurring micro-organisms such as bacteria, fungi and algae
Biodegradation	Degradation brought about by the action of naturally occurring micro-organisms such as bacteria, fungi and algae
BMW	Biodegradable municipal waste
Composting	A managed process that involves the biological decomposition and transformation of biodegradable material to produce carbon dioxide, water, minerals and organic matter (compost or humus)
CRT	Cathode ray tube
Defra	Department for Environment, Food and Rural Affairs
Degradation	A change in the chemical structure of a plastic involving a deleterious change in properties
EA	Environment Agency
EU	European Union
FAO	Food and Agriculture Organisation
FSC	Forest Stewardship Council
EfW	Energy from waste
EN 13432	European standard for packaging recoverable through composting and biodegradation
GHG	Greenhouse gas
GWP	Global warming potential
HDPE	High-density polyethylene
LDPE	Low-density polyethylene
LLDPE	Linear low-density polyethylene
LCA	Life Cycle Assessment. A process of assessing various environmental impacts of a product/service over its lifetime

PC	Polycarbonate
PE	Polyethylene
PET	Polyethylene terephthalate
PHA	Poly (3-Hydroxy Alkanoate)s
PHB	Polyhydroxybutyrate
PLA	Polylactic acid or polylactide
PP	Polypropylene
PTT	Polytrimethylene terephthalate
PU	Polyurethane
PVC	Polyvinylchloride

Executive Summary

Study Background

Bioplastic consumption is growing in the UK, with key drivers for their increasing use including: potential to offer the opportunity to reduce our reliance on fossil fuels; reduction in emissions of greenhouse gases (GHGs); enhanced technical and performance characteristics; EU legislative incentives such as taxation benefits and varying disposal options including composting. This project has been commissioned by Defra to review the environmental effects and market trends of bioplastics.

Project Objectives

The specific objectives of the project were to: Identify the range of bioplastics currently on the market or being developed and assess their current market situation; assess the environmental effects of a small number of bioplastics applications across their life cycle; compare the environmental effects of these to conventional plastics of the same application; clarify the types of bioplastic applications and different end of life scenarios that are likely to be the most advantageous to the environment, as well as being economically and socially feasible/ beneficial; and recommend ways to stimulate the use of these most advantageous scenarios.

Conclusions

This project has combined desk-research, stakeholder engagement and primary environmental research to assess the bioplastic market. Through multi-criteria assessment based on environmental, economic, technological, legislative and social information, the areas of opportunity and barriers have been identified. This assessment is made in reference to the bioplastics of PLA (film and durable applications), cellulose film, starch film, PHA (durable applications) and renewable PET. Each bioplastic was compared to one comparable conventional plastic.

Barriers to Bioplastics Uptake

- Resin costs and sales value – the bioplastics under investigation were found to be up to four times more expensive to produce and retail than the selected conventional alternatives. Prices are anticipated to reduce as efficiencies improve and the scale of production increases.

- Diversion to AD/composting – this route offers an opportunity for materials to be diverted from landfill, however it cannot yet be fully realised due to a lack of infrastructure, capacity and some AD facility operators not accepting bioplastics.

- Contamination of recycling streams – where used in formats that are recycled in the UK, bioplastics are seen as contaminants. PLA can be identified but with additional time and cost implications for separation facilities. Tests on other bioplastics have not been conducted.

- Production capacity – bioplastics currently represent around 0.7% of the global plastic market, this limits process efficiencies and economies of scale.

- Unsustainable use of land – additional land is required to produce bioplastics compared to conventional plastics. This is a drawback but only a barrier to production if the land is used unsustainably, as it is estimated that between 250-800 million ha of agricultural land could be brought into production without encroaching on ecologically or socially valuable land (FAO, 2008). Based on bioplastic production estimates up to 2020, this would only account for between 0.1-0.3% of this available land and as such land use is not a barrier to their use. However, if used unsustainably, on ecologically or socially valuable land or releases high amounts of stored carbon, this is seen as a barrier. It should also be noted that if bioplastics are sourced from land used to produce food crops there can be a perception barrier to their use.

- GHG emissions – cellulose film currently has higher GHG emissions than PP film.

- Mulch film removal from land – current UK legislation requires agricultural films to be removed from the land for disposal. Starch mulch is designed to be left on the land.

- Poor public understanding and identification – the public find it difficult to identify bioplastics and they have limited understanding of these materials.

- Landfill restrictions - Landfill Directive targets restrict the total amount of BMW going to landfill, which is a barrier to their use if not disposed of appropriately.

Bioplastic Opportunities

- Reduced GHG emissions – most bioplastics assessed offered lower GHG emissions than the conventional plastics[1]. This is greatest when they use less material or offer enhanced functionality, such as improved shelf-life.

- Reduced use of non-renewable resources – all the bioplastics reviewed were manufactured from renewable resources, therefore offering a potentially sustainable opportunity to reduce reliance on fossil fuels.

- Composting/ anaerobic digestion – most of the bioplastics assessed can be managed using these methods and therefore offer opportunities to divert waste from landfill.

- Agricultural film disposal – starch mulch was shown to offer environmental advantages over LLDPE, although it would need to be left on the land after use to realise these.

[1] Excluding the effects of indirect land use change, which have not been measured in most studies.

- Renewable conventional plastics disposal – these do not need to be distinguished from conventional plastics and as such do not impact the UK waste system.
- Job creation – bioplastics are anticipated to offer job creation in the agricultural sector (remaining steady in the manufacturing and lower supply chain stages). It is estimated that by 2020 20,000 new jobs globally could be created.

Recommendations

- Industrial co-operation – through industry-led initiatives across the full supply chain stakeholders can work together to increase bioplastic use. Suggestions include using standardised labelling or identification systems, a sustainability index, industry-led research (independently verified) into shelf-life benefits and increased dialogue through an independent body.
- Creating awareness – a programme of public and industry engagement to overcome and prevent misconceptions should be instigated combined with impartial advice to decision-makers regarding bioplastic opportunities and barriers.
- Policy interventions – use of a combination of policies and approaches which are clear and avoid uncertainties. Options include advising local authorities on bioplastic collections, enhanced public procurement standards, production incentives or grants/loans to SMEs.
- Further research – the conclusions made here are based on limited data and a fast-moving market and as such should be reviewed and updated regularly. Suggested additional research includes sustainable agricultural practices, use of non-food crops as feedstock, impacts of starch mulch film on the land and shelf-life benefits.

Limitations

This study has used a varied range of research techniques and whilst the data and information used to generate the study's conclusions and recommendations is believed to be the best available, it is considered to have limitations. These are:

- The assessment undertaken is based on the current level of bioplastic use, which represents around 0.7% of the global plastics market. If this market share increased, much of the data used to conduct the multi-criteria assessment would also change.
- The multi-criteria assessment makes comparisons between each bioplastic and one conventional plastic equivalent only, it should be noted that the conclusions drawn in the report could vary if other polymers or applications were assessed.
- Some data used within the project was based on a series of assumptions and estimates, which at the time were considered to be the most reasonable and justified.

- In some cases, data was not available to be assessed within all desired categories. These gaps, once again, meant assumptions were made or these aspects could not be assessed, placing uncertainty on the results.

1 Context

1.1 Study Background

Bioplastic consumption is growing in the UK, with key drivers for their increasing use including: potential to offer the opportunity to reduce our reliance on fossil fuels; reduction in emissions of greenhouse gases (GHGs); enhanced technical and performance characteristics; EU legislative incentives such as taxation benefits[2] and varying disposal options including composting.

This project has been commissioned by Defra to review the environmental effects and emerging market trends of bioplastics through a review of published material and engagement with stakeholders. This evidence and that based on the technical, social and economic impacts was evaluated to provide recommendations to overcome the barriers of bioplastic use where they offer opportunities over conventional plastics.

1.2 Context

The market for bioplastics is influenced by several factors. These include the opportunity to respond to the challenge of increased petrochemical plastic prices, which are directly linked to the price of crude oil; the opportunity to package food and non-food goods in a more sustainable fashion (evidenced by life cycle assessment); the opportunity for manufacturers to differentiate their product offering with a new class of materials and the opportunity to positively impact on greenhouse gas emissions of products.

Other opportunities may be policy driven and include the possibility to assist in the management of food waste, for example, by anaerobic digestion or composting. Biodegradable or compostable plastic containers of food waste or of food which has exceeded its shelf life could enter the same waste management regime as the food products themselves, thus simplifying or nullifying the need to segregate the food waste from its packaging or container.

Evidence to underpin these potential opportunities is scarce, unpublished or in some cases may not be robust. This study therefore sets out to address this lack of consolidated, robust evidence in this subject area. The outputs from this report are aimed to support Defra in their future policy-making surrounding the bioplastic market.

1.3 Project Objectives

Based on the overall aims of the project outlined above, the specific objectives of the project are to:

- Identify the range of bioplastics currently on the market or being developed - including their feedstocks, applications and common disposal routes.

[2] Those used in countries such as Belgium, Latvia, the Netherlands and Romania give reduced taxation on bioplastics compared to conventional plastics. This is detailed further in Section 4.4 of this report

- Assess the current market situation of each bioplastic application and identify emerging market trends and the driving forces behind these.

- Assess the environmental effects of a number of representative bioplastics across their life cycle.

- Compare the environmental effects of these representative bioplastics to a conventional plastic of the same application.

- Clarify the types of bioplastics, applications and different end of life scenarios that are likely to be the most advantageous to the environment, as well as being economically and socially feasible/ beneficial.

- Recommend ways to encourage/stimulate the use of these most advantageous scenarios to overcome any barriers to bioplastics.

1.4 Definitions

The term bioplastics is commonly used to describe two quite distinct classes of polymer:

Bio-based polymers are made in whole or in part from renewable resources, for example, sugar, starch, vegetable oils, cellulose, and also food residues. The concept is related to the "origin of the carbon building block", and the focus is on the need to switch from petroleum based resources to renewable ones in order to control greenhouse gas emissions.

Biodegradable polymers (that may be bio-based or not), are polymers that have some degree of inherent biodegradability, i.e. are decomposable by biological activity such as through bacteria or fungi, and give rise to natural metabolic products. In this case the concept is related to the "end of life and disposal" of polymeric materials, and the focus is on waste management techniques. Throughout this report where the term biodegradable is used, this is considered to be in line with the requirements of the composting standard EN 13432.

These two classes of bioplastics are not mutually exclusive. Bio-based polymers may be biodegradable or not, for example bio-polyethylene from bio-ethanol from Braskem is non-biodegradable, while regenerated cellulose, NatureFlex from Innovia, is biodegradable. Biodegradable polymers may be either bio-based, from petroleum origin or composites made of renewable and petroleum resources. For example, polylactic acid (from NatureWorks) is bio-based and biodegradable but polycaprolactone is non-renewable and biodegradable. All these examples are considered to be bioplastics within the definitions used by this study, only petrochemical-non-biodegradable polymers are not bioplastics.

2 Conclusions and interpretation

2.1 Conclusions

This project has combined a review of published material, stakeholder engagement and primary environmental research to assess the current and emerging bioplastic market. Through multi-criteria assessment based on environmental, economic, technological, legislative and social information, the areas of opportunity and barriers to using various key bioplastics have been identified. Where barriers have been found, the report goes on to make recommendations as to how these can be overcome.

2.1.1 Policy Review

- **Legislation**: No one policy measure will help develop the market. A series of initiatives need to be considered. These initiatives must impact the entire supply chain. Government purchasing schemes can act as incentives to industry to make investment decisions. Other mechanisms, such as guaranteed pricing helps to remove any uncertainty in the market place. However, it is important to avoid complicated schemes as this can lead to confusion.

- **Industrial cooperation**: The bioplastic industry needs to cooperate and collaborate to ensure that inconsistencies in approaches are avoided.

- **Financial support**: Grants can help support investment decisions, however revenue support is better for promoting commercial success.

- **Creating awareness:** Measures that help develop consumer awareness need to be considered. Brand owners are also key to creating awareness and can help develop the markets for bioplastics.

2.1.2 Barriers to Bioplastic Uptake

This study has identified a series of barriers which currently prevent the bioplastics investigated from occupying a larger share of the market. These are:

- **Resin costs and sales value**: the bioplastics under investigation were found to be more expensive to produce and retail than conventional alternatives. This ranged from cellulose and PLA being up to 50% more expensive, to starch and PHA reaching up to four times the price of conventional plastics. When used in durable applications, PLA was seen to offer an economic advantage over polycarbonate. However, this is likely to only be around 40% of the material used in such applications and the comparative costs of additives/ polymers are not accounted for.

It should be noted that as production efficiencies and economies of scale increase, the costs of bioplastics are anticipated to decline.

- **Diversion to AD/composting**: current potential opportunities in waste management through the use of composting and anaerobic digestion techniques cannot be fully realised due to; a lack of collection infrastructure; limited UK capacity; householder confusion in identifying bioplastics and concerns from some AD facility operators over conventional plastic contamination and process changes required to attain the required bioplastic degradation.

- **Contamination of recycling streams**: where bioplastics are used in formats that are currently recycled in the UK, they tend to be treated as contaminants, and have the potential to reduce the quality of the end product (various acceptable PLA limits have been identified in different studies: these range from 0.001% to 5%). It should be noted that bioplastics such as PLA can be positively identified and separated prior to reprocessing, but this would incur cost and time implications. Additionally, many of the packaging formats assessed, such as films or rigid non-bottle plastics, currently have recycling rates of only around 3% in the UK (Valpak Consulting, 2009); however, these levels are increasing.

- **Production capacity**: bioplastics currently represent around 0.7% of the plastics market, with a global production capacity of around 1.9 million tonnes[3] much of which is produced in relatively small plants. This compares to the 265 million tonnes of conventional polymers used in 2010[4]. This represents a barrier to the use of bioplastics in terms of volume restrictions but also in process efficiency gains, which relates to economic and in the case of cellulose, environmental barriers.

- **Unsustainable use of land:** in order to produce bioplastic feedstock additional land is required compared to conventional alternatives, this ranges from around $0.13m^2$ kg^{-1} for cellulose[5] to $3m^2$ kg^{-1} for PHA[6]. However, current land use is not always managed at optimal efficiency and it has been estimated that between 250-800 million ha of agricultural land could be used without encroaching on areas of high ecological or social value. Based on bioplastic production estimates up to 2020, this would only account for between 0.1-0.3% of this available land and as such land use is not a barrier to their use. However, if used unsustainably, on ecologically or socially valuable land or releases high amounts of stored carbon, this is seen as a barrier. It should also be noted that if bioplastics are sourced from land used to produce food crops there can be a perception barrier to their use.

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[3] Derived by the authors of this report based on public announcements and personal correspondence with manufacturers.

[4] Plastics Europe Market Research Group, April 2011

[5] Provided in personal correspondence by Innovia, 2010

[6] Omar et al, 2001 and Page, 1996

- **GHG emissions**: cellulose films currently have higher GHG emissions than conventional PP film equivalent packaging. Whilst this may change as process efficiencies improve, this is currently a barrier to using this material as it does not currently offer the environmental advantages seen by the other bioplastics researched.

- **Mulch film removal from land:** current UK legislation requires agricultural films be removed from the land for disposal. This represents a legislative barrier to the use of starch mulch, whereby it is designed to remain on the land and is likely to be irremovable as a result of the commencement of the degradation process. Whilst these restrictions remain in place, the opportunities offered by this bioplastic cannot be realised.

- **Poor public understanding and identification**: as a result of the public not being able to identify materials as bioplastics, segregation possibilities are restricted. Additionally, a lack of understanding concerning the materials is considered to limit consumers' willingness to pay for the materials.

- **Landfill restrictions**: the Landfill Directive sets targets which restrict the total amount of biodegradable municipal waste (BMW) going to landfill in 2020 to 35% of that produced in 1995. The disposal of bioplastics to landfill should therefore be avoided which is a barrier to its use if not disposed of appropriately.

2.1.3 Bioplastic Opportunities

This study has identified a series of opportunities offered by the bioplastics researched. These are:

- **Reduced GHG emissions**: most of the bioplastics assessed were found to offer lower GHG emissions over their life cycle compared to their conventional alternatives[7], for example PLA offers 30% less emissions compared to PP per kg on a cradle to gate basis. This opportunity is greatest in instances where the bioplastic currently offers the same performance using less material, such as starch mulch film which is three times lighter than an LLDPE film and where enhanced functionality is offered, such as shelf-life performance, which is currently claimed for PLA and cellulose in certain applications.

- **Reduced use of non-renewable resources**: all the bioplastics assessed use renewable feedstocks for production, and as such offer a reduction in the use of non-renewable resources. For example, the conventional polymers assessed use around 70-130MJ of fossil-fuels per kg of resin manufactured, which compares to most of the

[7] Excluding the effects of indirect land use change, which have not been measured in most studies.

bioplastics being under 10MJ per kg. As a result, bioplastics offer a potentially sustainable opportunity to reduce the reliance on non-renewable resources.

- **Composting/ anaerobic digestion**: most of the bioplastics assessed are compostable, and where UK recycling rates are poor (domestic film, non-bottle rigids and multi-layered materials) or packaging is heavily contaminated, this provides an opportunity to divert waste from landfill. However, this opportunity is restricted as outlined above, by limited UK collection and processing capacity, a lack of householder knowledge and facility operator concerns.

- **Agricultural film disposal:** starch mulch has been shown to offer an environmental advantage over conventional alternatives. This is primarily evidenced by the fact that three times less film is required, but they also do not require removal from the land for disposal. However, further research into the impacts of the mulch degradation on the land is required.

- **Renewable conventional plastics disposal:** these plastics, such as the renewable PET researched, offer an opportunity as they do not need to be distinguished by consumers as being different to conventional plastics. As a result, they do not require any changes to the current waste management system.

- **Job creation**: the use of bioplastics has been found to offer a social opportunity in the anticipated global net increase in jobs. The employment sector is estimated to remain steady in the manufacturing and lower supply chain stages, with the increase stemming from those jobs created in the agricultural sector. This increase is modest, estimated by 2020 to represent around 20,000 new jobs globally, but remains an opportunity for the bioplastic market.

It is acknowledged that the bioplastic assessment made in this report, and as such the conclusions drawn, are based on an incomplete dataset and that of a fast-moving market. As a result the conclusions should be reviewed at regular intervals.

2.2 Recommendations

The recommendations provided in this Section are a possible set of tools that could be used to increase the use of bioplastics in the UK, if this is seen as desirable in the future. These tools have been categorised into the key areas of industrial co-operation, creating awareness, policy and further research. As a result of the current political landscape those based on industry-led, voluntary initiatives as highlighted in the industrial co-operation category, are considered the most likely to be taken forward.

2.2.1 Industrial Co-operation

- Through an industry-led initiative across the full supply chain, stakeholders should work together in future-proofing operations for an increase in bioplastics on the market. The following suggestions are examples of suitable activities that could help in this area:
  - Development and support for a standardised labelling scheme, use of a unique colour or using bioplastic-based materials for certain applications only or UV-doping. Each of these options would allow for easier identification of bioplastics by consumers and waste managers but would require the support of the full supply chain to be a success.
  - Extension of the Courtauld Commitment to include a sustainability index, rather than a focus on GHG emissions only.
  - Industry led research into the potential enhanced properties of bioplastics, such as the extension of shelf-life, with the development of an external verification system.
  - Development and support for a labelling system based on various indicators of sustainability, including GHG emissions, non-renewable resource use, water use and land use for example.
  - Dialogue between packaging specifiers and the waste management sector, including research and development stakeholders. Having this awareness in the design stage will aid the acceptance of EN 13432 materials through AD/composting facilities and allow for the identification and segregation of bioplastics at reprocessing facilities, after which they would ideally be sent to AD/composting or bioplastic recycling technologies rather than landfill. Additionally an independent body could help the supply chain communicate through industry directories and stakeholder events.

2.2.2 Creating Awareness

- A programme of public and industry engagement is required to overcome and prevent any misconceptions surrounding bioplastics, for example, those relating to unsustainable land use or that of food crop land. Current views appear to consider all bioplastics as the same, when in fact they each have their own properties and opportunities.

- In terms of environmental benefits, bioplastics have been found to offer the greatest advantages when they can offer a reduced quantity of raw materials compared to conventional alternatives, or an enhanced performance in terms of shelf life, for example. Impartial advice to interested parties, such as brand owners/retailers, surrounding these opportunities should be made available and as noted above, this would require further research as the assessment made in this report only makes comparisons of each bioplastic with one conventional equivalent.

2.2.3 Policy Derived

- The lessons learnt from the Biofuels sector suggest that a combination of policies and approaches need to be considered to support the development of bioplastics. These policies must have an impact throughout the supply chain. They should be clear and easy to understand so as to avoid confusion. Programmes that help develop awareness with consumers and stakeholders are also important in this approach. Other key critical aspects to avoid are any uncertainties. Therefore mechanisms that can help reduce risk should be a priority.

- Further investigation is required into the preferred waste management route (with food waste or mixed plastics) for bioplastics. Guidance to local authorities should be provided on this in order to, as far as possible, facilitate consistency in collections.

- Any future public sector financial support to new designs for AD/composting facilities should only be provided if they have the necessary pre- or post-processing adaptations so they are capable of processing EN 13432 certified bioplastics effectively

- Introducing public procurement standards that assess environmental sustainability in more depth could be beneficial. European member states have been given political support to an increase in Green Public Procurement (GPP). The improvements have to be accomplished at the level of member states. UK Government could lead on GPP in line with the experience of the United States.

- Economic and production capacity barriers facing bioplastics could be addressed through:

    - Introducing a production incentive for bioplastics. Such credits already exist in Germany and are being introduced in France, resulting in the lack of an even playing field across EU member states. Such a mechanism for bioplastics should encourage investment, production, and adoption of bioplastics in the UK market.

    - Establishing grants and loans to small and medium sized enterprises would incentivise production plants and industrial processes for the use of bio-based feedstocks, provided that they have proven to be sustainable and that applicable EU State Aid rules are respected.

- ➢ This funding should also be directed to R&D as further work is needed to overcome some of these technical barriers, especially performance.

2.2.4 Further Research

- The conclusions and recommendations made in this study are based on an incomplete dataset and a fast-moving market; as a result they should be reviewed regularly, for example biennially.

- If AD/composting facilities continue to reject bioplastics as a feedstock, other recovery solutions such as mechanical biological treatment (MBT) could be researched and potentially supported to accept these materials and avoid them being diverted to landfill.

- In order to ensure feedstock for bioplastics is sourced from sustainable agricultural practices, Government should support and research international and national efforts to improve agricultural land productivity. This may include but not be limited to land use management, yield increases, reuse of degraded land, cropping systems etc. Manufacturers should find a suitable mechanism to illustrate to customers that their feedstock is sustainable, such as the sustainability index/label mentioned above.

- Support further research into the use of non-food crops to produce bioplastic feedstock such as grassland, waste crops and other biomass (for example shellfish waste).

- Further research is required into the use of starch mulch on agricultural land in the UK and the impacts of its degradation. If this is suitable, legislation surrounding the required removal of all mulch films from farm land should be reviewed and potentially amended to allow starch-based mulch to remain on the land.

- Further research into the benefits of improved properties, such as increased shelf-life, should be conducted. These features have the potential to enhance the environmental performance of the packaging considerably but require external verification.

- The development of Product Category Rules (PCRs) for both bioplastic and conventional plastic applications should be researched and published to support LCA methodologies. These would consider such issues as the inclusion of biogenic carbon, degradation rates and carbon accounting in land use. Such guidance would produce LCA results that are fairer and more comparable than are currently available publicly.

3 Methods and approach

This section presents an overview of the methods and approach used for this report in order to meet the study's objectives. It was carried out in four distinct phases, each of which is described below.

3.1 Phase 1 – Initial Bioplastics Research

This primarily involved a review of existing scientific research literature and other published material on bioplastics. Additionally, stakeholder consultation through telephone and email correspondence was used, to gather supplementary information not available in the public domain. The output of this phase was an assessment of the bioplastic market and the selection of seven specific bioplastics to be focussed upon for the remainder of the project.

3.2 Phase 2 - Environmental Assessment

Having identified seven bioplastics for further study, this project Phase involved conducting an in-depth environmental review using both secondary research and stakeholder contact. The quality of the evidence was assessed and gaps in research were identified and the potential need for additional primary research was recognised. This resulted in the requirement for three life cycle assessments (LCAs) to be carried out, where significant gaps in environmental data were observed.

3.3 Phase 3 - Stakeholder Workshops

In order to engage with stakeholders, a series of workshops were facilitated by Valpak Consulting. The objective of the workshops was to provide policy and technical input into the study and learn from the experiences and opinions of key stakeholders.

3.4 Phase 4 – Assessment of Barriers and Opportunities for Use

Information surrounding the use of policy instruments to support the bioplastics market outside of the UK was collected using desk-based research, and summarised. Consequently, all the information gathered throughout the project was consolidated to assess the barriers and opportunities to using bioplastics, based on environmental, economic, social, legislative and technological issues.

4 Results

4.1 The Bioplastic Market

The research conducted has identified a number of broad categories of bioplastics currently available on the market or in development. It is estimated that the current worldwide production of bioplastics is around 1 million tonnes, with the production capacity estimated to be approximately 1.9 million tonnes. This represents around 0.7% of the global plastics market and is detailed by key bioplastic category in Figure 1.

Figure 1 **Production Capacities of Bioplastics (tonnes / annum)**

	Worldwide Production Capacity	Worldwide Production	Notes
Polylactic acid (PLA)	155,000	100,000	NatureWorks (140,000) + Hisun (15,000); Pyramid (2012, 60,000) and Purac/Sulzer/Synbra have announced intention to produce 55,000-75,000 tonnes
Poly (3-hydroxy alkanoate)s (PHA)	90,000	<50,000	Metabolix has announced start up production of 50,000. DSM has announced 10,000 tonnes production intention. Tianan produces in the order of 2,000 tonnes
Bio-based Polyethylene/trimethylene terephthalate (PET/PTT)	100,000	Not available	Based on 45,000 tonnes production of bio-based 1,3-propanedioal and 1,2-ethylene glycol
Bio-based polyamide	50,000	<50,000	Arkema has more than 25,000 tonnes of product derived from castor oil
Bio-based polyethylene	200,000	0	Braskem + additional 350,000 in 2011 announced by Dow
Bio-based polyurethane	Not available	Not available	There is no bio-based polyurethane production in the UK
Bio-based polypropylene	0	0	Braskem announcement but no tonnages and no timescale
Polycarbonate (derived from CO_2)	150,000	15,000	All from sequestered CO_2
Starch	165,000	<100,000	Starch occurs usually in blends with biodegradable polyesters (this number includes bio-polyester content [Ecoflex 74,000 tonnes])
Cellulose	1,000,000	800,000	Comprising 30,000 tonnes of film from Innovia (regenerated cellulose); remainder cellulose diacetate and triacetate for cigarette tow and LCD screens respectively
Lignin	5,000	5,000	Reconstituted lignin/cellulose composites (Tecnaro)
Total	**1,915,000**	**1,080,000**	75% of this production figure comprises traditional cellulose di- and tri-acetate manufacture

4.2 End of Life Options

Five end of life options for bioplastics were investigated for the project, with the key conclusions made being:

- Landfill - This is an undesirable disposal option due to the release of methane during decomposition under anaerobic conditions for most bioplastics and its place in the waste hierarchy.
- Incineration with EfW - A potentially worthwhile route due to the high GCV of plastics and that bioplastics contain biogenic, rather than fossil-based carbon.
- Composting - Most biopolymers are compostable in industrial installations and/or at home in some situations. This offers the potential for reduced collections and the treatment of food residue without separation. Labelling offers guidance to this, but confusion has resulted over whether biopolymers can be composted at home or in an industrial composting facility.
- AD - This waste treatment offers the advantages of energy production and further diverting waste from landfill. As a new technology AD capacity is currently limited in the UK and some operators have concerns over bioplastic inclusion within their feedstock due to contamination by conventional plastics for example.
- Recycling - Only PLA recycling has been investigated due to this being the only bioplastic which has undergone such trials. The separation and recycling of PLA by NIR separation has been found to be successful but likely to incur additional costs. In order to maintain a good quality conventional plastic stream, various acceptable PLA limits have been identified in different studies: these ranged from 0.001% to 5%.

4.3 Environmental Review

Based on the research presented above, the Consortium, through discussions with Defra, selected the following seven bioplastics/applications for detailed environmental review and the focus of the remainder of the project:

- PLA multilayer film from Natureworks
- PLA durable goods
- Starch food waste bag from Novamont
- Cellulose film from Innovia
- Starch agricultural mulch from Novamont

- Renewable PET bottle from the Coca-Cola Company
- PHA casings

A total of 10 LCAs and six environmental summaries were found to relate to one of the entities selected for detailed review. The key results arising from this assessment are detailed by bioplastic/application below.

4.3.1 PLA Film

- Three LCA studies were found to relate to PLA film. Two were cradle to gate analyses considering the production of the Ingeo™ pellet only (Vink et al 2003 and 2007) and a further study was a full LCA of a PLA multi-layer film (Vidal 2007).
- Up to pellet production, lower energy and water use was seen for PLA than conventional plastics. An improvement in these differences was seen between the 2003 and 2007 studies.
- For the multi-layer film, lower GWP and fossil fuel depletion were seen for the biopolymer compared to conventional plastic film. Eutrophication impacts were higher for the PLA.
- An LCA of a PLA multi-layered film (composed of PLA and PVOH for use in packaging fresh fruit and vegetables) was carried out by Valpak Consulting to supplement this information for use by the bioplastic manufacturer and Defra.

4.3.2 PLA Durable Goods

- No studies were found to relate to automotive parts or cell-phone cases, although these products are relatively widely used.
- One study was found to cover a Fujitsu PLA laptop cover (Kimura and Horikoshi, 2005) and identified this as producing 15% fewer CO_2 emissions when combusted compared to a conventional plastic cover. If recycled the PLA cover was shown to reduce CO_2 emissions by 29%. This study was not considered robust by the project team.

4.3.3 Starch Bag

- Three LCAs and four environmental summaries covering the impacts of starch bags were reviewed (Morken & Nyland 2002, Estermann and Schwarzwalder 1998, Estermann 1998, James and Grant 2002, Ademe 2002, Imperial College 2007 and Mohee et al 2007).

- In general, although there were variations between all of the LCA studies, an apparent trend is that bio-based polymers do offer some environmental benefits, including the reduction in use of fossil energy resources and reduced greenhouse gas emissions when the optimal waste management options are used.
- The dominant source of environmental impacts associated with biodegradable bags appears to be the extraction and production of the base raw materials.
- Landfilling of biopolymer based bags emerged as a less favourable waste management option due to the release of methane from anaerobic degradation. Incineration with EfW was the disposal option which resulted in the lowest environmental impact for the single use biopolymer based bags.
- The fossil fuel polymer based bags have higher resource impacts (abiotic depletion).
- Global warming potential was higher when starch bags were used to collect waste that is destined for landfill.

4.3.4 Starch Mulch Film

- No studies specifically covering mulch applications of Mater-Bi® material were found.
- An LCA completed by Novamont and Valpak Consulting was carried out for use by the bioplastic manufacturer and Defra.

4.3.5 Cellulose Film

- One environmental summary produced by Innovia (2007) was found, but this provided only comparative data and no absolute values and referred to a cradle to gate analysis.
- An LCA carried out by Innovia and Valpak Consulting was used to supplement this information for use by the bioplastic manufacturer and Defra.

4.3.6 Renewable PET bottle

- One full LCA has been conducted but it is not in the public domain. There is only some summary data on carbon emissions available indicating 25% fewer emissions compared to conventional PET bottles (Coca-Cola Company 2009).

4.3.7 PHA

- Three LCA studies for PHB were reviewed as part of this study. PHB is a type of PHA (PHA is a class of polymer - there are 150 PHA polymers with slightly different structures). PHB is one of the most common ones and as such the results of these studies are seen as indicative. Two studies considered a cradle to gate analysis (Harding 2007 and Kim and Dale 2008) and a further study was a full LCA considering a CRT monitor housing and automotive panels (Pietrini 2007).

- When considered from cradle to gate, PHB is seen as having reduced GHG emissions and non-renewable energy consumption when new technology is considered.

- One study found a GHG credit to be produced as a result of energy recovery within the fermentation process (Kim and Dale 2008).

- On a cradle to grave basis, the chosen application and its conventional plastic equivalent appears to be significant in determining environmental benefits, with the CRT monitor housing being superior to its conventional alternative which was high impact polystyrene (HIPS), whereas the automotive part was not based on it being compared to a PP-based panel.

4.4 Policy Instruments

This section of the report aims to provide an overview of the current policy and legislative initiatives that support the use of bioplastics in the EU, USA and UK. The aim of this review is to highlight concepts that might be relevant for the development of a UK framework.

4.4.1 Lead Market Initiative

The European Commission's Lead Market Initiative aims to facilitate the early adoption of innovative technologies. The initiative recognises that market entry for new technologies is difficult, however if barriers can be lowered it becomes possible to build early markets of sufficient scale that help to justify investments. In 2009 an Ad-hoc Advisory Group for Bio-based Products published a report on the measures that could be used to promote bio-based materials. The Advisory Group used the European Commission’s Lead Market

Initiative[8] as a framework. This report summarised a number of policy and legislative actions that would be of benefit to the bio-based industry. The executive summary includes 6 recommendations; 1) legislation promoting market development; 2) product specific legislation; 3) legislation relating to biomass; 4) green public procurement; 5) standards and certification and 6) financing & funding of research.

4.4.2 German Packaging Ordinance

In Germany, packaging legislation is dealt with through the German Packaging Ordinance. Under these regulations businesses are required to submit annual declarations detailing packaging placed onto the German market, have agreements with licensed collection and disposal systems and ensure take-back of all packaging. Within these regulations there is support for packaging made from biodegradable materials. If all the components are compostable and independently certified to the appropriate test standards, the manufacturers do not have to pay the license fees imposed by the packaging recycling systems. However, the producers and distributors of this packaging still have to ensure that a maximum fraction of these materials is being recycled.

Similarly if producers and distributors participate in collection systems and have packaging that has a renewable raw material content of 75% or more, which is also biodegradable, they can be excluded from the mandatory deposit scheme operated in Germany for one-way beverage packaging.

4.4.3 Taxation Benefits

Taxation benefits are seen as an important policy tool in the promotion of bioplastics in a range of applications. Such credits already exist in Germany, Italy and Belgium and more are on the way in France[9]. Therefore, the playing field is not level across the EU member states. The initiative provides a production tax credit for bioplastics with the intention to encourage investment, production, and adoption of these materials in a developing market. For example, in Italy biodegradable mulch films are subject to a 16% reduction in VAT compared to conventional films.

Figure 2 is a summary of taxation types and levels for The Netherlands, Latvia, Romania and Belgium, which have been selected based on the availability of tariff information. The majority of those below have adopted a scheme with lower tariffs for biobased materials such as wood, paper and bioplastics.

[8] http://ec.europa.eu/enterprise/policies/innovation/policy/lead-market-initiative/

[9] https://ktn.innovateuk.org/web/polymers/articles/-/blogs/some-key-findings-from-our-bio-plastics-for-packaging-event-with-the-west-midlands-rfa;jsessionid=2E66846CA0F18F4762681A447D27971D.9OphEwv4

Figure 2 **Taxation by Country**

Country	Tax Type	Units	Tariff
Netherlands	Packaging	€ per kg	Plastic = 0.4705 Bio Plastic = 0.079502
Latvia	Natural Resources	€ per kg	Plastics= 0.92 Bio Plastics = 0.21
Romania	Tax on bags	€ Per bag	0.04
Belgium	Eco tax	€ per kg	Exception saving €3/kg

Direct intervention against existing petrochemically derived products has also been used as an incentive for bioplastics. A number of countries have banned the use of conventional but not bioplastic carrier bags. In 2002, the Irish government passed a tax on plastic bags, which resulted in a 94% reduction. Similar approaches have been used in other countries with varying success. The Irish success could be attributed to the steep tax at 33 cents per bag and the fact that plastic bags were not manufactured in Ireland. Therefore, there were no strong political or economic arguments that hampered its implementation.

4.4.4 BioPreferred Programme

European member states have given political support to an increase in Green Public Procurement (GPP). The improvements have to be accomplished at the level of member states. In the USA, a voluntary labelling and procurement program, The USDA BioPreferred[10] Programme, arose from the 2002 Farm Bill. It seeks to increase the take-up, purchase and use of renewable, environmentally friendly bio-based products, whilst providing "green" jobs and new markets for farmers, manufacturers, and retailers. The programme has demonstrated a number of successes in bioplastics. This approach has resulted in further legislation and the USA is leading the development of biofuels, with a new legislation bill that encourages consumers to switch.

4.4.5 Courtauld Commitment

In the UK, an approach being adopted by the grocery sector is called the Courtauld Commitment. The Commitment encourages the grocery retail industry to adopt a series of voluntary targets that are linked to the reduction in the environmental impacts of packaging products.

The Courtauld Commitment is a voluntary agreement aimed at improving resource efficiency and reducing carbon emissions. The Courtauld Commitment Phase 1 commenced in 2005 with an aim to look at new solutions and technologies so that less food, products and

[10] http://www.biopreferred.gov/?SMSESSION=NO

packaging ended up as household waste. This has moved on to the Courtauld Commitment Phase 2 which was launched on 4th March 2010. The new approach adopted in Phase 2 moves away from solely weight-based targets and aims to achieve more sustainable use of resources over the entire lifecycle of products, throughout the whole supply chain.

This commitment is supported by a total of 29 major retailers and brand owners. Engagement with supporters of this agreement may be beneficial for the bioplastic industry as there might be opportunities to promote the benefits these materials offer in lower GHG emissions.

4.4.6 Renewable energy policies

The renewable energy sector in the UK is established and could help provide some benchmarks for policy and legislation within the bioplastics sector. The energy sector has utilised a combination of policies to reduce the impacts throughout the supply chain. Incentive tariffs that guarantee price, government purchasing schemes that act as incentives to industry, sales tax rebates and consumer grants or rebates are just some of the polices and measures adopted by this sector.

The most successful of these initiatives have been the ones that have helped to reduce uncertainty in a developing market e.g. long term contracts with guaranteed unit returns for set prices. Inconsistencies in policies were seen as a major problem of regulation especially if a set of measures had different impacts in the same market place.

In the renewable energy sector legislation was seen to help provide the catalyst for change in a developing market. However, it was recognised that it was vital that the correct policies were adopted and that inconsistencies were avoided.

4.5 Identification of Barriers & Opportunities

A multi-criteria assessment software package (V.I.S.A)[11] was used to aid the decision making process in identifying barriers and opportunities in bioplastics researched as part of this project. This software was used to compare each bioplastic with a corresponding conventional plastic application in relation to each defined criterion. Seven comparison scenarios were created in the assessment tool for the modelling and analysis, based on available data and LCAs, as shown in Figure 3.

Figure 3 Comparison Scenarios

Scenarios	Bioplastic	Conventional Plastic
1	PLA multi-layered film	PP rigid / film
2	Cellulose film	PP film
3	Starch mulch	LLDPE mulch film
4	Starch bag	HDPE bag
5	PHA casing	Polycarbonate casing
6	PLA laptop casing	Polycarbonate casing
7	Renewable PET bottle	PET bottle

11 http://www.visadecisions.com/

The criteria and sub-criteria used to evaluate the plastics were decided upon based on discussions with the project Steering Committee and through stakeholder engagement, although they were partially limited by available data. The criteria used were:

- Environmental – GHG emissions, land use, non-renewable resource use
- Economic – resin costs, sales value
- Technological – fit with the current waste management system, production capacity
- Legislative – incentives, penalties
- Social – job creation

A full description of the methodology and data used within this assessment, as well as its robustness, is provided in the accompanying Technical Report.

4.5.1 PLA Multilayered Film & PP Rigid/Film

Based on the multi-criteria analysis it is clear that the PLA film offers environmental opportunities through a potential reduction in GHG emissions and use of non-renewable resources and, similar to all of the bioplastics, a potential for job creation through approximately 2,600 posts globally in 2020[12]. Based on the cradle to gate data available, PLA is seen to have around 30% less GHG emissions than the PP per kg of material. Another opportunity not included in the main assessment due to a lack of verified data, is that manufacturers claim the PLA multi-layered film offers shelf-life benefits. As the food contained within such packaging often has much higher GHG emissions than the packaging itself, this represents a further opportunity for the bioplastic. However, this potential benefit does require further research and independent verification.

The barriers identified from the analysis are shown to exist primarily from the economic and technological categories. PLA was shown to be around a third more expensive in terms of both the resin cost and sales value of the material compared to PP film, which is a significant barrier to its uptake. For example, PLA resin is seen to cost around $1.3-1.9 per kg compared to PP which is around $1.2 per kg. However, it should be noted that based on historical data if the price of oil reaches and is sustained at around $85 a barrel then PLA can become cost-competitive with oil-based plastics in the USA.

From a technological perspective there are both barriers and opportunities to using the PLA film in the current waste management system. In terms of being directed to landfill or incineration/EfW, from a technological perspective the bioplastic is not seen as being any different to the conventional alternatives, although under incineration does benefit from biogenic rather than fossilised carbon emissions[13]. If the PLA entered the recycling stream, a barrier is identified for several reasons. Firstly, to identify the film as PLA would require process alterations by separation facilities as it is difficult to identify visually, which would

[12] As detailed and explained in Figure 13 of the Technical Annex

[13] This assessment is based on technological rather than environmental criteria, however it should be noted that under landfill conditions PLA was found to show practically no degradation, similar to conventional plastics (Valpak Consulting 2010a)

have cost and time implications. Secondly, if the PLA was not segregated it would reduce the quality of the end product if used in significant quantities (studies suggest tolerance levels of anything from 0.001% to 5% contamination (CONTREP, 2007, Natureworks 2009 and van Keyenberg 2006)). Finally, whilst PLA being recyclable is an opportunity, there is no PLA recycling infrastructure in the UK to treat it separately. This compares to the PP rigid or film, which whilst does currently have a very low recycling rate in the UK, is being increasingly collected from households and is recyclable as part of the mixed plastics stream[14].

If the bioplastic were composted or anaerobically digested an opportunity is seen as the conventional alternatives have poor recycling rates and do not have the option of this disposal route, which diverts waste from landfill. However, whilst this opportunity is evident, based on the current waste management infrastructure in place in the UK[15], the volume of material entering these streams is low, UK capacity is also low[16] and there are other potential barriers, such as some AD operator's fears that conventional plastics will contaminate the process or that pre- or post-processing will be required to allow the bioplastics to break down as required.[17]

A drawback to bioplastics is the use of additional land (around 1.7m^2 per kg in the case of PLA) to produce the feedstock not needed for conventional plastics and this has the potential of being diverted from food crop uses. However, this is not seen as a barrier to their uptake as current land use is not always managed at optimal efficiency and according to the FAO between 250 and 800 million ha of land globally could be brought into production without encroaching upon areas of high ecological or social value (FAO, 2008). Whilst they do put a caution on these figures, based on the projected level of PLA use in 2020 and its land take, this would be only 0.02% of the available land (based on all bioplastic projected capacities in 2020 only 0.1-0.3% of this land is estimated to be utilised.) It should however be noted that this would be a barrier to the use of bioplastics if land is used unsustainably, through converting land that is of high ecological or social value or that would result in a release of a large amount of stored carbon.

As with most of the bioplastics, in terms of UK legislation there is considered to be no penalties or incentives currently available for the use of PLA, however Landfill Directive targets do restrict the total amount of biodegradable municipal waste (BMW) going to landfill in 2020 to 35% of that produced in 1995. The disposal of bioplastics to landfill should therefore be avoided which is a barrier to its use is not disposed of appropriately.

4.5.2 Cellulose & PP Film

The analysis revealed that cellulose film offers potential opportunities but also barriers in most of the main criteria assessed. Key opportunities are seen environmentally through a reduction in the use of non-renewable resources, socially through creation of jobs and technologically in the potential for composting/AD.

[14] Based on the currently proposed changes to the Packaging Regulations with separate targets for plastic bottles and other plastics, this recycling has potential to increase over the next few years.

[15] In 2008-09 only 31% of local authorities offered a food waste collection service (http://www.wrap.org.uk/downloads/Household_food_and_drink_waste_in_the_UK_-_report.e18baddd.8048.pdf)

[16] Currently the UK has 11 AD plants processing approximately 320,000 tonnes of food waste (ENDS Report 426, July 2010), although over the next five years another 600,000 of new capacity is anticipated.

[17] Based on data collected by WRAP for 'Review of Biodegradability of BS EN 13432 Certified Bags in AD and IVC Systems' 2010.

Similar to PLA, barriers are seen in terms of the pulp costs and sales value of the material being higher (in this case by approximately 25-50%) and from waste management in terms of recycling for the same reasons outlined above for PLA. However, it should be noted that no studies have been carried out to assess the impact of cellulose on the recycling stream and as such this requires further clarification, although based on trials carried out on behalf of WRAP it is known that the material would be considered a contaminant in the film recycling process (WRAP, 2009).

In addition to the above, cellulose has a barrier in terms of the GHG emissions emitted over its life cycle, which are higher than those for an equivalent PP film. Whilst this is a current barrier, the production of all bioplastics suffer from efficiency limitations and are undergoing improvements, which offer the potential to improve their environmental performance; however, without the demand for the material these are likely to be restricted and the improvements required to reduce the GHG emissions to the level emitted from conventional plastics is unknown. Another related opportunity is that the manufacturer Innovia claims that the bioplastic has the ability to improve the shelf-life of fresh foods. As the food contained within such packaging often has much higher GHG emissions than the packaging itself, this represents a further opportunity for the bioplastic, but does require further research and independent assessment.

In terms of land use, once again this is a drawback for the bioplastic, however it is not seen as a barrier due to the large amount of available land identified if used sustainably and without converting ecologically or socially valuable land (as outlined above). Additionally, Innovia claim their product to be made entirely of FSC certified wood, representing the sustainable nature of the feedstock.

4.5.3 Starch Mulch & LLDPE Film

The use of starch as a mulch film, once again, is shown to offer opportunities in terms of GHG emissions, use of non-renewable resources, waste management and job creation. It was found that three times less starch mulch film was required for use on the same area of land as the LLDPE due to it being thinner, which does partially account for some of the environmental benefits identified. Interestingly, the starch and LLDPE have the same GHG emissions per kg of material manufactured on a cradle to gate basis. However, over the full life cycle the emissions are higher per kg of starch as a result of those generated as the mulch film degrades on the land. Nevertheless, as three times less material is required for the starch mulch compared to the conventional mulch film, overall the GHG emissions are lower.

In contrast to the other bioplastics, starch mulch film offers an opportunity in terms of waste management. The starch mulch film is designed to be left on the land after use and as such does not require removal for waste management, which is likely to be landfill or recycling. Novamont, the manufacturer, claims that is it unlikely to be possible for the starch to be removed after use due to the degradation process commencing[18], and as such would not reach recycling or other waste treatment processes. Whilst the current recycling rate of agricultural films is approximately 20% and likely to increase if the planned Producer Responsibility Regulations on these materials are introduced (Defra, 2009), the LCA used to estimate the GHG emissions of the materials identified that even at a rate of 50% recycling,

[18] Based on personal dialogue with Novamont 2010

the bioplastic provided the lower emissions option as it requires less material compared to the LLDPE. This is despite the fact that per kg of material the starch end of life GHG emissions are actually higher.

A significant barrier to realising the waste management and environmental opportunity outlined above is identified in the assessment through a current legislative penalty. Currently in the UK, all agricultural films are required to be removed from the land to be disposed of via landfill or recycling. As a result, the mulch film is not able to be used in the UK at present as it cannot be removed from the land based on its degradation. Therefore, this represents a barrier to the use of this film in the UK.

As with PLA and cellulose, starch was found to be more expensive to produce and have a higher selling price than the conventional LLDPE mulch film; in this case being up to approximately twice the price per kg sold. However, as noted above there would actually be less starch used per hectare compared to LLDPE and additionally, no associated removal/ disposal costs. In a recent study on strawberry use in Italy, Piedmont (2010) found the cost per ha of LDPE mulch film to be around €1,500 compared to starch, which was around €1,050. It should be noted that additional transportation costs would be incurred for importing the starch to the UK from Italy. Nevertheless, overall, the starch mulch film is competitive with the conventional mulch, based on sales value.

Production capacity for starch in non-food applications was found to be lower than that of LLDPE and as such is highlighted as a barrier to the use of starch. Whilst in general terms this is true, again it is important to note that less starch is required per hectare and Novamont claims that they have enough production capacity for this product to cover the total mulch film market.

Once again the use of land was seen as a drawback but not a barrier to using starch film, where around 1.9m^2 is required to produce 1kg, which has the potential to be used for food crops. Once again it is important to note that it has been estimated that the potential area of land required for the use of bioplastic production is very small in comparison to the 250 to 800 million ha believed to be available (FAO, 2008).

4.5.4 Starch Bag & HDPE/PE Bag

When using starch as a food waste bag it is shown to present opportunities in terms of GHG emissions reductions, being over 20% less than HDPE bags (James and Grant, 2002), waste management with AD/composting options and job creation where around 3,000 jobs are estimated to be created in starch production globally by 2020[19].

In terms of waste management the bags have been seen to offer a greater environmental impact if they are landfilled with Morken and Nyland (2002) finding that starch bags to release over two times the GHG emissions of a PE equivalent bag under these conditions, however in terms of the technological implications, this route is not affected by using a bioplastic. In terms of recycling the starch bag, similar to the other bioplastics, this has potential to cause contamination. Nevertheless, it is designed to be part of a structured food waste disposal programme and as such should be routed to the appropriate composting/AD facility, which represents an opportunity. However, once again these services to households

[19] As detailed and explained in Figure 13 of the Technical Annex

are restricted[20] and some AD operators have been shown to have concerns about the use of these food bags[21], which currently does represent a barrier to this potential management. Additionally, there is potential for these bags to be collected for recycling with conventional polyethylene bags and as such contaminate the recycling process, which once again is seen as a barrier.

Economic barriers to the use of starch bags are identified through higher resin costs and sale prices of up to four times that of conventional bags, with starch resin being around $1.6-4 per kg compared to HDPE which is around $1 per kg. This is partially related to the lower production capacities identified for the starch compared to HDPE bags, where starch (in non-food applications) is believed to have a global capacity of around 60,000 tonnes, compared to HDPE bags which are estimated to have a capacity of around 7.8 million tonnes22. Environmentally, the land use take, which could potentially be from food crop sources, is also a drawback once again but not seen as a barrier, for the reasons noted above. Finally, as with the other bioplastics Landfill Directive targets restrict the BMW going to landfill which is a barrier for these materials if not managed appropriately.

4.5.5 PHA & Polycarbonate Casing

The assessment of PHA and polycarbonate casings for electrical equipment was primarily conducted using cradle to gate data, based on a lack of market information on the specific applications. Based on this, the PHA was found to offer environmental opportunities in terms of lower GHG emissions and use of non-renewable resources. The GHG emissions data reviewed for this study varied depending on which conventional polymer and application it was compared to, but in comparison to a polycarbonate on a cradle to gate basis, polycarbonate was seen to have emissions of 7.6 kg CO_2e per kg (PlasticsEurope, 2010) compared to PHA, which in one study, was found to have a negative carbon footprint of 2.3 kg CO_2e per kg, based on its production process actually generating energy (Kim and Dale, 2008). Based on the same sources, PHA was found to use around 2MJ of non-renewable resources compared to a polycarbonate at 113MJ per kg on a cradle to gate basis, however the authors of this work did assume large amounts of agricultural residues to be used for providing process heat, which could make this comparison unfair.

PHA also has a potential social benefit through job creation. PHA was identified as offering the highest potential global job increase of around 15,000 posts created[23], as its feedstock, sugar cane, and predicted production levels in 2020, create the highest level of agricultural employment among the bioplastics examined.

Based on the materials being used in electronic applications and the UK waste management infrastructure for waste electricals being recently developed as a result of the Waste Electronic and Electrical Equipment (WEEE) Directive, the material is equally likely to be diverted to recycling whether it is made of the conventional plastic or bioplastic. There is a possibility that the PHA could contaminate the recycling stream; however, as such products require dismantling and pre-treatment it is less likely to cause a problem than in other

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[20] In 2008-09 only 31% of local authorities offered a food waste collection service (http://www.wrap.org.uk/downloads/Household_food_and_drink_waste_in_the_UK_-_report.e18baddd.8048.pdf)

[21] Based on data collected by WRAP for 'Review of Biodegradability of BS EN 13432 Certified Bags in AD and IVC Systems' 2010.

[22] Based on HDPE bags accounting for around 26% of global HDPE capacity of 30 million tonnes, estimate from http://www.chemsystems.com/reports/search/docs/abstracts/0506_3_abs.pdf

[23] As detailed and explained in Figure 13 of the Technical Annex

applications. As a result, this material is considered to neither present an opportunity or barrier in terms of the recycling stream. It also still has the potential to be anaerobically digested or composted after shredding, which offers a further opportunity, although this is currently prevented as a result of the issues discussed above. Polycarbonate can be challenging to recycle and as such there is potential for the PHA to offer environmental savings in this stage of the life cycle. However, further research is required to investigate this potential opportunity.

PHA was found to face an economic barrier based on higher resin costs, being around twice those estimated for the conventional plastics, where PHA resin is seen to cost around $5.8-7.3 per kg compared to polycarbonate at $3.05-3.12 per kg. It is worth bearing in mind that in most applications PHA can be combined with other co-polymers and as such these costs also need to be accounted for.

The land use required for the production of PHA is a drawback compared to conventional polymers, which is estimated to be around $3m^2$ per kg of PHA (Omar et al, 2001 and Page, 1996), and is potentially from food crop sources. Whilst it has the largest area of land required per kg of feedstock of the bioplastics assessed, it still represents only around 0.02% of the land seen as available for agricultural purposes by 2020 based on future production estimates. As a result, land use is not seen as a barrier to its use, if the land is managed sustainably.

4.5.6 PLA & Polycarbonate Casing

Comparing the use of PLA to polycarbonate resulted in almost the same assessment of barriers and opportunities as those identified above for PHA. The only difference seen was that relating to the economic assessment, where the PLA was found to offer a slightly lower resin cost and sales value compared to the polycarbonate, where PLA is around $1.3-1.9 per kg of resin and polycarbonate is around $3.05-3.12 per kg. However, it should be noted that PLA durable materials are often composites and the compostability and sales value of the material will be related to the other polymers with which they are combined. Within a typical PLA durable product PLA represents around 30-40% of the material used, with the remaining 60-70% of the material being made of other polymers or additives. Therefore, whilst the costs and GHG emissions of the PLA are seen as lower compared to the polycarbonate, it is the additives and other polymers and their own costs and emissions which will determine if the PLA or polycarbonate are cheaper or have lower GHG emissions; however this will vary widely by the composition/application.

Overall, it is difficult to assess the key barriers and opportunities as they are impacted greatly by the polymers/additives used in conjunction with the PLA.

4.5.7 Renewable PET Bottle & PET Bottle

There was only limited information available regarding the PET bottle for the assessment; however certain opportunities and barriers have been identified. Firstly, the renewable bottle is claimed to have 25% fewer GHG emissions than the conventional alternative and as such does offer an environmental benefit. Additionally, the bottle is said to be completely compatible with the current UK recycling processes and as such, based on the criteria, does not have any of the barriers, which are potentially affecting the other bioplastics.

The renewable bottle does have land use as a drawback to its use, being estimated to take around $0.9m^2$ per kg produced (Rosa, 2005), with the potential for its feedstock to have been sourced from food crop land. However, this is not seen as a barrier to its use, as noted above. However, as with the other bioplastics, the production capacity is much lower than the conventional PET bottle, which does represent a barrier to its use.

Whilst no economic data for the renewable PET bottle could be found, through anecdotal evidence it is believed to be more expensive than the conventional bottle in both its production cost and sales value, which therefore does represent another barrier to its uptake.

5 Limitations

This study has used a varied range of research techniques to identify the main barriers and opportunities of using bioplastics in the UK. Whilst the data and information used to generate the study's conclusions and recommendations is believed to be the best available, it is considered to have limitations. These are:

- The assessment undertaken is based on the current level of bioplastic use, which represents around 0.7% of the global plastics market. If this market share increased, much of the data used to conduct the multi-criteria assessment would also change, for example, the greenhouse gas emissions, job creation, land-use requirements and economic assessment. As a result the opportunities and barriers would also potentially be altered.

- The multi-criteria assessment makes comparisons between each bioplastic and one conventional plastic equivalent only, it should be noted that the conclusions drawn in the report could vary if other polymers or applications were assessed.

- Some data used within the project was based on a series of assumptions and estimates, which at the time were considered to be the most reasonable and justified. Each key piece of data used was assessed for its robustness to highlight any uncertainty, as detailed in the Technical Report which supports this report.

- In some cases, data was not available to be assessed within all desired categories. These gaps, once again, meant assumptions were made or these aspects could not be assessed, placing uncertainty on the results.

- Aspects of the data used have a natural variability, such as economic information and production levels. Averages were taken to reduce the impact of these variations, but nevertheless this is a further limitation to the results.

- Much of the data used within the study was only available from one source, for example, the manufacturer, of which for many bioplastics there is only one. This meant that verification of the data was not always possible and is therefore a further limitation to the results; this is reflected in the assessment of the data's robustness provided in the supporting Technical Report.

Annex A: Technical Report

1 Context

1.1 Introduction

This document forms The Valpak Consulting Consortium's Technical Report for 'Bioplastics: Assessing their environmental effects, barriers and opportunities'.

The activities detailed within this report were undertaken by a research consortium, made up of Valpak Consulting (lead contractor & project manager), the BioComposites Centre from Bangor University (sub-contractor), the Centre for Sustainable Chemical Technologies from the University of Bath (sub-contractor) and Bowman Process Technology (sub-contractor).

1.2 Study Background

Bioplastic consumption is growing in the UK, with key drivers for their increasing use including: potential to offer the opportunity to reduce our reliance on fossil fuels; reduction in emissions of greenhouse gases (GHGs); enhanced technical and performance characteristics; EU legislation using incentives such as taxation benefits[24] and varying disposal options such as composting.

This project has been commissioned by Defra to review the environmental effects and emerging market trends of bioplastics through a review of published material and engagement with stakeholders. This evidence and that based on the technical, social and economic impacts was evaluated to provide recommendations to overcome the barriers of bioplastic use where they offer opportunities over conventional plastics.

1.3 Context

The market for bioplastics is influenced by several factors. These include the opportunity to respond to the challenge of increased petrochemical plastic prices, which are directly linked to the price of crude oil; the opportunity to package food and non-food goods in a more sustainable fashion (evidenced by life cycle assessment); the opportunity for manufacturers to differentiate their product offering with a new class of materials and the opportunity to positively impact on greenhouse gas emissions of products.

Other opportunities may be policy driven and include the possibility to assist in the management of food waste, for example, by anaerobic digestion or composting. Biodegradable or compostable plastic containers of food waste or of food which has exceeded its shelf life could enter the same waste management regime as the food products themselves, thus simplifying or nullifying the need to segregate the food

[24] Such as reduced taxation given to bioplastics compared to conventional plastics in countries such as Belgium, Latvia, Romania and the Netherlands. This is detailed further in Section 4.6 of this report.

waste from its packaging or container. Additionally, where demonstrable and verifiable environmental benefits accrue, markets may be stimulated by public procurement activities akin to the Bio-preferred scheme that operates in the United States or the Lead Market Initiative which is underway in Europe. These policy drivers will be discussed in detail in section 4.6 of this document.

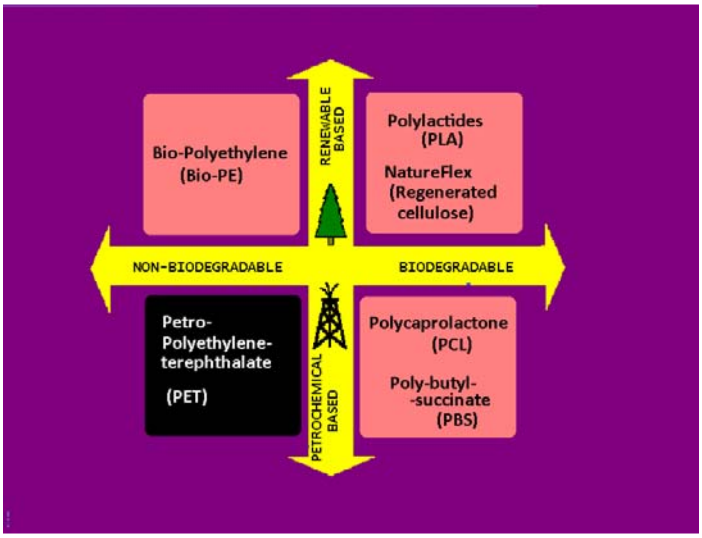
1.4 Definitions

The term biopolymers (often used interchangeably with bioplastics), is commonly used to describe two quite distinct classes of polymer:

Bio-based polymers are made in whole or in part from renewable resources, for example, sugar, starch, vegetable oils, cellulose, and also food residues. The concept is related to the "origin of the carbon building block", and the focus is on the need to switch from petroleum based resources to renewable ones in order to control greenhouse gas emissions.

Biodegradable polymers (that may be bio-based or not), are polymers that have some degree of inherent biodegradability, i.e. are decomposable by biological activity such as through bacteria or fungi, and give rise to natural metabolic products. In this case the concept is related to the "end of life and disposal" of polymeric materials, and the focus is on waste management techniques.

Figure 1 Biopolymer Cross



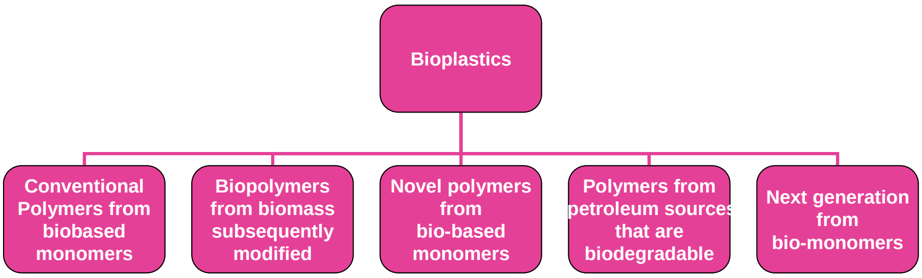
To be classified as bio-based, a material must be organic and contain some percentage of recently fixed (new) carbon found in biological resources or crops. This definition is the basis of a new EU standard presently under discussion (EN 15440) and of the US equivalent ASTM D6866.

Biodegradable or compostable plastics are those which meet all scientifically recognised norms for biodegradability and compostability of plastics and plastic products independent of their carbon origin. In Europe, the composting standard is EN 13432 and in the USA it is ASTM D6400[25]. Throughout this report where the term biodegradable is used, this is considered to be in line with the requirements of EN 13432.

These two classes of bioplastics are not mutually exclusive, as indicated in Figure 1. Bio-based polymers may be biodegradable or not, for example bio-polyethylene from bio-ethanol from Braskem is non-biodegradable, while regenerated cellulose, NatureFlex from Innovia, is biodegradable. Biodegradable polymers may be either bio-based, from petroleum origin or composites made of renewable and petroleum resources. For example, polylactic acid (from NatureWorks) is bio-based and biodegradable, polycaprolactone is non-renewable and biodegradable while the different Mater-Bi® grades are blends of starch - a renewable material and non-renewable engineering polymers (polycaprolactone, polyvinyl alcohol, etc.). Only petrochemical-non-biodegradable polymers are not bioplastics.

The following diagram illustrates the major classes of bioplastics based on the definitions set out above, where the final group ‘next generation from bio-monomers’ is used to capture any new bioplastics not yet on the market which may not fit into the other four categories.

Figure 2 Types of Bioplastics



Based on these definitions, the following broad categories of bioplastics have been identified and included within this study, and are detailed in section 4.2 of this report (Figure 3):

- Poly Lactic Acid (PLA)

- Poly (3-Hydroxy Alkanoate)s (PHA)

[25] There is a difference between the two notions, biodegradable is a broad concept, while compostable refer to specific process conditions. A *biodegradable* material is capable of being completely broken down under the action of microorganisms into carbon dioxide, water and biomass. It may take a very long time for some material to biodegrade depending on its environment (e.g. wood in an arid area versus paper in water), but it ultimately breaks down completely. Many contaminating materials not dealt with in common composting are in fact "biodegradable", and may be dealt with via bioremediation or other special composting approaches.
A *compostable* material biodegrades substantially under specific composting conditions. It is metabolized by the microorganisms, being incorporated into the organisms or converted into humus. The size of the material is a factor in determining compostability, and mechanical particle size reduction can speed the process. Large pieces of hardwood may not be compostable under a specific set of composting conditions, whereas sawdust of the same type of wood may be. Compostable materials are biodegradable under very specific conditions, usually either within an industrial process, or in a home compost situation. The differences between the two are related to temperature and time of degradation.

- Bio-Based Polyethylene terephthalate (PET)
- Polytrimethylene terephthalate (PTT)
- Bio-Based Polyamide
- Bio-Based Polyethylene
- Bio-Based Polyurethane
- Bio-Based Polypropylene
- Polycarbonate (derived from CO_2)
- Starch
- Cellulose
- Lignin

2 Objectives

2.1 Project Objectives

The overall aim of the project is to investigate the bioplastic market, including their life cycle environmental effects and to identify the main barriers and opportunities of using these materials in the UK.

The specific objectives of the project are to:

- Identify the range of bioplastics currently on the market or being developed - including their feedstocks, applications and common disposal routes.
- Assess the current market situation of each bioplastic application and identify emerging market trends and the driving forces behind these.
- Assess the environmental effects of between three and five representative bioplastics across their life cycle.
- Compare the environmental effects of these representative bioplastics to conventional plastics of the same application.
- Clarify the types of bioplastics, applications and different end of life scenarios that are likely to be the most advantageous to the environment, as well as being economically and socially feasible/ beneficial.
- Recommend ways to encourage/stimulate use of these most advantageous scenarios to overcome any barriers to bioplastics.

3 Methods and approach

3.1 Introduction

This section presents the methods and approach used for this report in order to meet the project study's objectives. It was carried out in four distinct phases, each of which is described below.

3.2 Phase 1 – Initial Bioplastics Research

This phase involved three steps:

3.2.1 Desk Based Research

This included a review of existing scientific research literature and other published material on bioplastics. The research was divided into two key aspects of bioplastics: a molecular and synthetic viewpoint detailing the technical developments of using renewable feedstocks and a physical viewpoint detailing the effects of those bioplastics manufactured downstream in the supply chain.

3.2.2 Stakeholder Consultation

A consultation approach was taken to supplement the desk based research. The consultees included representatives of the manufacturing, packaging and retail industries. Telephone interviews were used to gather supplementary information not available in the public domain.

3.2.3 Bioplastic/ Application Selection

This phase involved discussions with Defra to determine the types of bioplastics or applications that would be focussed upon for the rest of the project.

3.3 Phase 2 - Environmental Assessment

This phase involved three steps:

3.3.1 In-Depth Environmental Review

An in-depth environmental review was carried out using both secondary research and stakeholder contact, to identify and collate all environmental data available on each bioplastic/application that was identified in the preceding project phase.

3.3.2 Data Quality & Gap Analysis

The robustness of each environmental study was rated using a set of developed quality indicators, based on Defra's Five Components of Robust Evidence. In addition, research based on LCA techniques were critiqued using an assessment based on compliance with the ISO 14040 series. Having assessed the quality of the data, gaps in robust research were identified and the potential need for additional primary research was recognised.

3.3.3 Further Primary Research

As a result of the gaps in data identified during this phase, further primary research was undertaken by Valpak Consulting. This involved the full LCA of three bioplastics, as follows:

- Cellulose film – a comparison of the full life cycle environmental impacts of Natureflex film and a conventional plastic film (OPP), for packaging peppers. The study included various waste management options and a shelf life assessment.
- PLA multi-layer film – a comparison of the full life cycle environmental impacts of PLA/PVOH packaging with a conventional non-biodegradable plastic (PP/PVC), for packaging mushrooms. The study included various waste management options and a shelf life assessment.
- Starch mulch – a comparison of the full life cycle environmental impacts of a starch mulch film compared to that made of LLDPE.

3.4 Phase 3 - Stakeholder Workshops

In order to engage with stakeholders, a series of workshops were facilitated by Valpak Consulting. The objective of the workshops was to provide policy and technical input into the study and learn from the experiences and opinions of key stakeholders.

3.5 Phase 4 – Assessment of Barriers and Opportunities for Use

The bioplastics' barriers and opportunities were assessed based on environmental, economic, social, legislative and technological issues. This assessment included information collected through the desk-based research and stakeholder interviews.

A multi-criteria assessment tree was then developed to assist in the identification of key barriers to and opportunities for the use of bioplastics. Each criterion of the assessment tree was weighted and then used to score each of the applications against the criterion. The resulting scores assisted with the identification of the greatest barriers and opportunities presented by each bioplastic assessed. This phase also involved assessing the bioplastics/applications in a legislative context. This was in order to identify any additional policy derived barriers or opportunities relevant to this study.

4 Results / Analysis

4.1 Introduction

This section of the report provides the results and analysis of the study carried out in each of the phases described in the methodology section above.

It includes an overview of the eleven types of bioplastics studied in relation to their main applications, feedstock, production process and current market situation. It also presents the study findings on the bioplastic market including prices and production capacities, disposal options, an environmental review and finally the assessment of key barriers and opportunities.

4.2 Bioplastics Overview: Application, Feedstock, Production Process and Current Market

An overview of the twelve types of bioplastics identified in this study is provided in the table below in relation to their applications, feedstock, production process and current market situation.

Figure 3 Bioplastics Overview: Application, Feedstock, Production Process and Current Market

Polymer	Main Applications	Feedstock and raw material	Production Process	Market
Polylactic Acid (PLA)	• bottles • disposable goods • films	PLA is produced from lactic acid. Lactic acid is primarily used in the food industry and is generally produced through fermentation of starch derived from corn, wheat or potatoes. Lactic acid can also be produced from the fermentation of sugars.	PLA is produced in two forms: a low and a high molecular weight.	• Natureworks – capacity 140,000 t a-1 • Fujitsu/Toray facility capacity 5,000 t a-1 • Hisun – capacity 15,000 t • PURAC 75000 t a-1 lactide production capacity by 2012 announced in 2010 (Thailand)
Poly hydroxy alkanoates (PHA)	• bottles • packaging (including films) • shopping bags • containers • paper coatings • disposable items • medical garments • upholstery and carpets • compostable bags, lids and tubs	PHA is produced by bacteria from within the cell. The bacteria can be grown on glucose, other sugars, lipids or agricultural waste. Current research has focussed on producing PHA from transgenic plants, though no commercial enterprise yet exists, the industrial production of PHA from plants would reduce the production costs by a factor of 10, lowering the price of PHA to be comparable with PE or PP.	PHAs are produced by microbial fermentation. There are over 150 types of monomer but the common polymers are PHB, PHBV, P3HB4HB, PHBHHx and mcl PHA. Both wild and engineered strains are used to produce the polymer and are grown on sugar, glucose or lipids. GM plants are in the development stage. These plants can produce large amounts of PHA at a fraction of the cost of the original process	PHA production is still relatively small; however, Metabolix capacity 50,000 t a^{-1}) and Kaneka (10-50,000 t a^{-1}) contain the largest market share. Tianan in China also produces this material.
Bio-Based Poly ethylene / trimethylene terephtalate (PET / PTT)	PET: • bottles • fibres PTT: • electronic connectors, plugs, sockets and switches • automotive parts • leaf screens • power tool components • furniture	PET is currently synthesised from terephthalic acid (or ester) and ethylene glycol both of which are derived from petrochemical sources. Bio-PET is the same polymer; however, the ethylene glycol is produced from sugar or starch derived ethanol. PTT is synthesised from terephthalic acid and 1,3 propanediol derived from corn starch.	Bio-PET is produced for the Coca-Cola company and is used to produce the 'PLANTBOTTLE'. The process produces 25% less CO_2 than the original petrochemical derived bottle. Bio-PTT is produced by Du Pont under the trade name Sorona.	Coca Cola introduced the PLANT BOTTLE in 2009 for the Dansai water range, which is to be expanded to other ranges later in 2010. The estimated production total of PET is 20,000 t a^{-1}. DuPont runs the worlds largest aerobic fermentation plant to produce 1,3 PD (45000 t a^{-1}). This is then reacted with Terephthalic acid or DMT to produce bio-PTT. India Glycol has also announced production of bio-derived ethylene glycol for PET production.
Bio based polyamide	PA11: • airbrake and electrical tubing • fuel lines • oil and gas pipes • shoes • electronic devices • catheters PA x, 10: • automotive • electrical	Polyamide 11 is produced after a multistep chemical reaction from a fatty acid prevalent in castor oil. The oil is extracted from the toxic seed of the plant,that can potentially be grown on land unsuitable for food production in India, China or South America. Polyamide x,10 is also derived from castor oil but with the addition of a non renewable amine.	Polyamide 11: Castor oil is pyrolyzed yielding 10-undecenoic acid, which is reacted with hydrogen bromide and ammonia yielding the amine monomer. Polyamide x,10: Castor oil is heated with an alkali catalyst which breaks the ricinoleic acid down in to sebacic acid. This can then be reacted with an amine to produce the desired polymer.	Fujitsu has entered into a joint venture with Arkema. Fujitsu plans to produce laptop covers and other computer / automotive parts with this or related polymers. PA-11 has been cleared for use in automotive fuel lines, including those with high biofuel contents.

Polymer	Main Applications	Feedstock and raw material	Production Process	Market
Bio based polyethylene	Bio based polyethylene is identical to its petroleum counterpart. Any density type can be manufactured and as such bio based polyethylene can be used as a direct substitute in all the same applications.	Bio-polyethylene is produced from an ethylene monomer, formed from the dehydration of bioethanol. Currently ethanol is obtained from the fermentation of sugarcane in the Tropics, wheat starch from within the EU or corn starch in the USA. Future feedstocks will be available to produce ethanol from agricultural waste or cellulose in the near future, reducing the competition with agricultural land set aside for food production.	Bio-polyethylene is manufactured in an identical manner to the petrochemical counterpart after the ethylene has been produced from bio-ethanol.	Over 50 million tonnes of ethanol was produced in 2008, though primarily as a transport fuel. Braskem has built a polyethylene production facility capable of producing 200,000 t a^{-1} of polyethylene in Brazil. Solvay is also building a production plant for the synthesis of PVC from ethanol in India; the facility will have a 60,000 t a^{-1} capacity. Dow has announced 350,000 t capacity for polyethylene.
Bio based polyurethane	• foam • insulation • elastomers • furniture and bedding • carpets • footwear • adhesives • sealants	Polyurethane can be produced from castor oil or from vegetable oils such as rapeseed, soybean or palm oil.	There are four main production processes possible: • Oxidation and epoxidation of vegetable oils • Polyols by hydroformulation • Polyols by ozonolysis • Polyols by transesterification	The Dow chemical company has produced a soybean oil based polyol in the production of polyurethane (Renuva), which claims to use 60% less fossil fuel than a conventional polyurethane. Production is still limited at present.
Bio based polypropylene	• packaging including films • textiles • durable consumer goods • automotive • fibres	Bio-polypropylene is produced from the polymerisation of propylene derived from syngas. The syngas is produced from the gasification of biomass, typically lignocellulose.	Pyrolysis of biomass results in the formation of CO and H_2 (syngas). The syngas is then converted to propylene using a Fisher-Tropsch process.	Syngas fuels and chemicals are still relatively expensive and as such there are no large scale manufacturers of polypropylene via this route. Braskem has plans to introduce a bio-based polypropylene to the market in the near future.
Polycarbonate (from CO_2)	• CDs • bottles, glasses • lab equipment • eye and sunglasses • electronic casing • hard sheets and films	Polycarbonate can be produced from CO_2 , derived from carbon capture technologies.	Two polymers are produced from CO_2. Poly(aromatic) carbonate is produced from the co-polymerisation of CO_2 and bisphenol A, poly(aliphatic) carbonate is produced from the polymerisation of an epoxide, which can be derived from biomass, with CO_2.	Chimei-Asahi Corp own a 150,000 t a^{-1} production capacity plant in Taiwan to produce poly(aromatic) carbonate. Currently poly(aliphatic) carbonates are produced in smaller volumes in the USA from Empower Materials and Novomer/Kodak, using CO_2 and epoxides.
Starch	Starch bioplastics are normally blended with polyester to form: • sheets and films • compostable bags • rigid articles	Starch is derived from corn, wheat and potatoes	Generally, the starch starting material must be physically or chemically altered to produce a useful polymer. The type of alteration, as well as the heat, water content and additional polyol content determine the properties of the starch polymer.	The use of starch polymers as a commercial biodegradable product is still hampered by water sensitivity and manufacturing costs. However, in 2005, starch based products were the most used biodegradable polymer, with just over 45,000 t a^{-1} produced. Novamont is the largest producer of starch based components and blends, selling them under the blanket trade name Mater-Bi®.

Polymer	Main Applications	Feedstock and raw material	Production Process	Market
Cellulose	Cellulose acetate: • fibre • film • tool handles • optics CAP, CAB: • durable consumer goods • packaging • biomedical applications	Cellulose is generally produced from wood, though it is also technically possible to produce refined cellulose from grasses and other plants.	Cellulose film (cellophane) is synthesised industrially from wood pulp. NaOH is used to break the crystalline structure, which is further reacted with CS_2 and the solution is then gelled with acid. The film is plasticized with glycols and water In the manufacture of Cellulose acetate polymers; wood pulp is deconstructed through mechanical means. The 'fluffy pulp' is then reacted with acetic acid (or longer chain acids) and acetic anhydride. This process also uses sulphuric acid. A controlled partial hydrolysis follows, and the polymer is dissolved in acetone. The polymer can then be processed into films as the acetone evaporates off.	The global market for cellulose acetate is over 1,000,000 t a^{-1}. However, the market for the film is nearer 45,000 t a^{-1}
Lignin	• computer and television casing • telephones	Lignin polymers are currently produced from wood.	The lignin is thermally processed and then blended with cellulose to produce a composite polymer with consistent properties, which is 100% renewable.	Currently, 5000 t a^{-1} is manufactured by Tecnaro GmbH under the trade name Arboform.

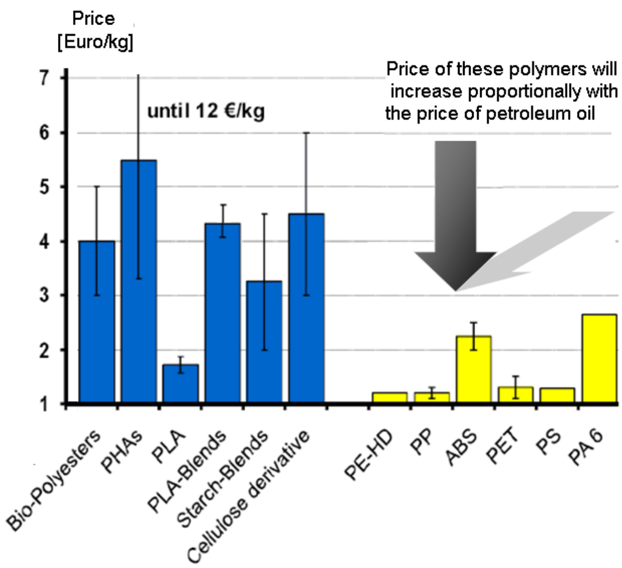
4.3 The Bioplastic Market: Prices & Production Capacities

This sub section provides insight into the current costs of biopolymers in comparison to conventional plastics. The current and future bioplastic market size and trends are then discussed.

4.3.1 Bioplastic Prices

The current prices of major biopolymers and conventional polymers are provided in Figure 4. It is clear that emergent bioplastics, at present, are more expensive than petroleum-derived polymers.

Figure 4 **Current Prices of Biopolymers and Petroleum-Derived Polymers (2009[26])**



The Figure shows that biopolyesters (an essential constituent of both PLA and starch blends used to make films) are more expensive than starch (the latter presently priced at 0.35 euros per kilo) and PLA. However, this situation is expected to be dynamic with petroleum-derived polymer prices increasing faster than bio-based ones. Oil corresponds to 40-80% of the price structure of petroleum-derived polymers but to a far lower value of bio-based materials. As such, PLA supplied by Natureworks at the price of USD1.50/kg, is expected to be cheaper than PET when the price of a barrel of oil is USD75 or higher. Additionally, bioplastics are anticipated to become more cost effective with increased economies of scale and through technological advances.

Historical data indicates that the PET price is more dependent than PLA on the price of oil, and that when the price of a barrel of crude oil was between USD80-90, PLA was cost competitive with PET. This scenario is expected to return over the coming

[26] Compiled from private correspondence with manufacturers and end users and attendance at sales events.

years, with the November 2008 International Energy Agency report stating that "*oil prices will rebound to more than USD100 a barrel as soon as the world economy recovers, and will exceed USD200 by 2030*".

The current prices for modified starch polymers range from €1.50 per kg for injection moulding foams to €4.50 per kg for films and speciality products. The average price is around €2–3 per kg. According to Bastioli (2003), the cost of native starch is not the overriding factor in the cost structure of polymer production. Rather, the cost is to be found in the modification process and therefore in the additives and co-polymers used in the blends, which in the case of compostable blends, are mostly engineering polymers. Due to this, starch polymers are bound to be more expensive than petroleum-derived polyolefins and bio-based polyolefins.

It is important to note that the price of bioplastics will increase as the price of oil increases but not at the same rate as for petroleum-derived polymers. This is because the price of oil corresponds to 40-80% of the price structure of petroleum-derived polymers but to a far lower percentage of bio-based materials.

4.3.2 Bioplastic Production: Applications & New Production Capacities

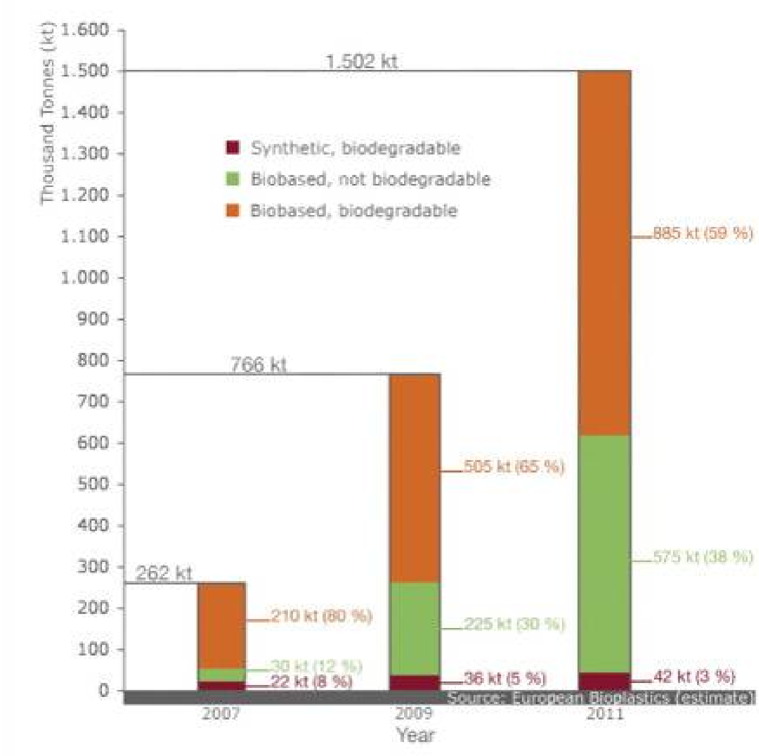
In addition to the food packaging market, bioplastics have known end-uses in the textile market (e.g. non-woven fibres), agricultural market (mulch film, erosion control netting, plant pots, and plant clips), consumer goods market (personal care, cosmetic packaging, cards, razors, brushes, applicators, cell phones, hygienic products [diaper back sheets, sanitary towels], pens and office supplies), automotive parts, electronics and building materials.

According to the European Bioplastic Federation, the global production capacity of bioplastics (excluding cellulosic) in 2009-2010 was estimated to be around 750k-1,5M tonnes[27]; a very small fraction (less than 0.7%) of the global plastic market (of 265M tonnes[28]). This is illustrated in Figure 5.

[27] We have not been able to reconcile the figures presented by European Bioplastics with our own estimates of global production capacities as set out in Figure 6.

[28] Plastics Europe Market Research Group, April 2011

Figure 5 **Production Capacities of Bioplastics (European Bioplastic Federation)**



4.3.3 Bioplastic Production: Market Growth

European Bioplastics suggests that the market potential in Europe alone could reach 5M tonnes in 2020, which is a 10% share of the total plastics market, assuming no overall growth. The drivers for growth include demonstrable and verifiable sustainability benefits, end of life management and policy incentives such as the Lead Market Initiative (discussed further in Section 4.6 of this report).

Additionally, it is believed that price has an increasingly important part to play as the long term trend for the price of oil is upwards; economies of scale for the production of bioplastics occur; and processing and manufacturing efficiencies develop. To achieve a 10% market share would require a year on year growth rate of 35%. According to Germany-based Helmut Kaiser Consultancy, the global bioplastics market is growing at 20% - 30% per year, and will jump from 200,000 tonnes in 2006, to 5M tonnes by 2015. A 2007 report from US-based BCC Research forecasts the global bioplastics growth rate at 17% per year from 245k tonnes in 2007 to 600k tonnes by 2012. The global market for all thermoplastics is estimated to be about 170M tonnes per annum, whilst the rate of growth of the conventional thermoplastic market is estimated to be 5%.

Shen et al. produced predictions of the future bioplastic market based on questionnaires, personal communications and through industry associations with over 32 companies from April 2008 and March 2009. This data was supplemented with company announcements and information obtainable in the public domain. The questionnaire was primarily based on their projections of the planned capacity expansions (L. Shen, et al., 2009, L. Shen, et al., 2010). From this study, the predicted production capacity would rise to 3.45 Mt by 2020, which is in line with a growth of 19% per annum. The four major bioplastics produced, totaling over 90% of bioplastic production anticipated, are expected to be starch, PHA, PLA and bio-PE. Under favourable economic conditions and government incentives, the researchers reasoned that global production of bioplastics could rise to be as high as 4.4 Mt in the same timeframe.

Research by Markets and Markets into the Global chemicals market (2009), suggests the move to de-couple economic growth from using non-renewable resources will help grow the sector from $45bn in 2009 to $59bn in 2014. Worldwide production and capacities are summarised in Figure 6. However, it should be noted that all the capacities indicated refer to company announcements that may not be implemented.

Figure 6 **Production Capacities of Bioplastics (tonnes / annum)**

	Worldwide Production Capacity	Worldwide Production	Notes
Polylactic acid	155,000	100,000	NatureWorks (140,000) + Hisun (15,000); Pyramid (2012, 60,000) and Purac/Sulzer/Synbra have announced intention to produce 55,000-75,000 tonnes
Poly (3-hydroxy alkanoate)s (PHA)	90,000	<50,000	Metabolix has announced start up production of 50,000. DSM has announced 10,000 tonnes production intention. Tianan produces in the order of 2,000 tonnes
Bio-based Polyethylene/trimethylene terephthalate (PET/PTT)	100,000	Not available	Based on 45,000 tonnes production of bio-based 1,3-propanedioal and 1,2-ethylene glycol
Bio-based polyamide	50,000	<50,000	Arkema has more than 25,000 tonnes of product derived from castor oil
Bio-based polyethylene	200,000	0	Braskem + additional 350,000 in 2011 announced by Dow
Bio-based polyurethane	Not available	Not available	There is no bio-based polyurethane production in the UK
Bio-based polypropylene	0	0	Braskem announcement but no tonnages and no timescale
Polycarbonate (derived from CO_2)	150,000	15,000	All from sequestered CO_2
Starch	165,000	<100,000	Starch occurs usually in blends with biodegradable polyesters (this number includes bio-polyester content [Ecoflex 74,000 tonnes])
Cellulose	1,000,000	800,000	Comprising 30,000 tonnes of film from Innovia (regenerated cellulose); remainder cellulose diacetate and triacetate for cigarette tow and LCD screens respectively
Lignin	5,000	5,000	Reconstituted lignin/cellulose composites (Tecnaro)
Total	**1,915,000**	**1,080,000**	75% of this production figure comprises traditional cellulose di- and tri-acetate manufacture

4.4 The Bioplastic Market: End of Life

The Waste Framework Directive (2008/98/EC) provides the framework for the collection, transport, recovery and disposal of waste. It requires all Member States to take the necessary measures to ensure that waste is recovered or disposed of without endangering human health or causing harm to the environment and to consider the waste hierarchy priorities when assessing the end of life options for all materials, including bioplastics[29]. This includes the prevention or reduction of waste production and its harmfulness, the recovery of waste by means of recycling, re-use or reclamation or any other process with a view to extracting secondary raw materials, or the use of waste as a source of energy.

Recent data indicates that between 2,363k and 2,520k tonnes of plastic packaging were consumed in the UK during 2009, with an estimation of 307k tonnes being collected from non-consumer sources and 259k tonnes collected from households. The household recycling is achieved by collecting 40 to 43% of plastic bottles and around 3% of other mixed plastics (Valpak Consulting 2009) placed in the household waste stream.

For conventional plastics, many disposal options are available including landfill, recycling, incineration with energy recovery and selective combustion of high calorific value plastics. Bioplastics also have many end of life options, which will depend on their physical properties, application, local infrastructure for collection and processing and legislative controls in place. Each option is outlined in the following sections.

4.4.1 Landfill

As the least favoured option, government policy aims to reduce the quantity of material being disposed of in this way. The landfill of some bioplastics can lead to emission of methane, a potent greenhouse gas, on their decomposition in anaerobic conditions (Song et al. 2009). In addition, the Landfill Directive restricts the total amount of biodegradable municipal waste (BMW) going to landfill in 2020 to 35% of that produced in 1995. The disposal of bioplastics to landfill should therefore be avoided.

4.4.2 Incineration with Energy Recovery

Due to their high gross calorific value (GCV), incineration with energy recovery is a potentially good disposal route for plastics especially bioplastics[30], after all recyclable elements have been removed. Starch and cellulose bioplastics have a lower GCV which is similar to that of wood, but still have some value in incineration.

[29] This Directive is currently under review by the Government, with changes including the replacement of 'reuse' by 'preparing for reuse' within the waste hierarchy. The revised Directive is anticipated to be transposed into UK law in 2010.

[30] Based on bioplastics containing biogenic rather than fossil-based carbon

4.4.3 Composting

In contrast to conventional plastics, most current biopolymers are compostable and fulfil the requirements of the EN 13432. However, some are compostable only in industrial composting installations, while others can also biodegrade in home composting bins. Biodegradation depends on temperature and time; home composting is performed at a lower temperature (usually lower than 30 °C) and requires relatively longer processing times. PLA is not considered home compostable as it only degrades in industrial composting situations, where the temperature is high enough (around 60 ºC). It can be mineralised to CO_2, water and a small amount of biomass, typically after a period of 4-6 weeks. Starch and cellulose films, and most polyesters reported in Section 4.2 are both home and industrially compostable and can be degraded in an anaerobic digestion chamber.

The current UK standard BS EN 13432 (2000)[31] applies only to packaging composted under conditions typically found in an industrial composting facility. Compliance with this standard is required to claim that a product is compostable in the European marketplace and allows use of the label shown in Figure 7.

Figure 7 BS EN 13432's Scheme's Certification Mark (logo) 'Compostable'

The ASTM 6400 standard is the regulatory framework for the US and sets a lower threshold of 60% biodegradation within 180 days, also within commercial composting conditions.

The 'compostable' mark indicates that the package complies with either of the two standards mentioned above. The marking is not owned by either regulatory body but by third party trade associations: in Europe, this is European Bioplastics, whereas in the U.S. this is the Biodegradable Products Institute. Many starch based plastics and PLA based plastics have obtained these certificates.

Home composting using bins or heaps is considered a suitable option for some packaging bioplastics, which can complement industrial installations and ease the

[31] EN 13432 requires that for a material or product to be defined as biodegradable it must fulfil the main following criteria: conversion to CO_2, water and biomass via microbial assimilation; biodegradation of over 90% compared with standard (cellulose) in 180 days under conditions of controlled composting using respirometric methods (ISO 14855); disintegration of less than 10% to be retained by a 2mm sieve (ISO 16929 and ISO 20220); and safety tests must be carried out for quality, ecotoxicity (for aquatic and terrestrial organisms such as *Daphnia magna*, worm test, germination test) and heavy metal content results on the produced compost.

pressure on household waste collection systems. However, it is difficult to regulate home composting and as such it may result in anaerobic digestion of the material and hence the production of methane.

Additionally, as noted above, some bioplastics certified for industrial composting to EN 13432 may not biodegrade sufficiently in home composting conditions (Song et al. 2009); hence, this distinction must be made aware to the public. Recent research by Song et al (2009) who conducted home composting trials, concluded that most starch-based polymers do biodegrade in home composting. However, PLA-based plastics were found to be unsuitable for biodegradation in home conditions.

There are no standards for home compostability; however, there is a private accreditation system, the OK Compost HOME standard from Vincotte, as shown below. It is similar to EN13432 except that the temperature requirements are lower and the time for disintegration is longer.

Figure 8 **Vinçotte's 'OK Compost Home' logo**

WRAP is launching a new Home Composting Label. The products certified by the OK Home Compost will be entitled to carry the label (shown in Figure 9) by applying to AfOR (Association for Organics Recycling) for approval.

Figure 9 **WRAP's Home Composting Label**

4.4.4 Anaerobic Digestion (AD)

AD means the conversion of organic, non-wood based material into useful and stable compounds in the absence of oxygen. It is a developing technology and the current UK capacity is therefore limited. Feedstocks include food wastes, slurry and biodegradable plastics. The outputs from the digestion are biogas, which can be combusted to generate heat, power or fuel and digestate, which is inert and nutrient-rich. This treatment offers the advantages of energy production, disposal of bioplastics and food waste together, diversion from landfill (avoiding the cost and space implications) and legislative incentives such as the Renewables Obligation.

A recent study concluded that the economics of AD for bioplastics are variable but improving (NNFCC 2008). It was considered a great potential for biopolymer disposal, with efficiencies of scale being considered important. However, recent research by WRAP has identified that facility operators do have concerns over the impact of bioplastics on their process and potential contamination of conventional plastics[32].

4.4.5 Mechanical and Chemical Recycling

Chemical recycling is claimed by Natureworks to be the best approach to a cradle-to-cradle system for PLA. This process involves the recovery of PLA, hydrolysis to an oligomeric fraction and subsequently to lactic acid, which could be reused in the production of more PLA. The UK producer of a PLA bottle for mineral water (Belu bottle) collects waste bottles from commercial premises (hotels, etc) and exports them to Galactic in Belgium, where they are recycled back to lactic acid. Similar processes could be used (in theory) to recycle bio-polyesters, but there is no published information assessing the potential for doing this. Mechanical recycling of starch blends is a standard practice during formulation and recovery of excess products. Only PLA has been investigated in specially designed laboratory research.

The collection and processing of waste bioplastic materials should be considered when assessing their recycling infrastructure. Where there are conventional plastics manufactured from renewable sources, they will simply form part of the reprocessors' feedstock. For new bioplastics such as PLA, PHA, PCL etc, it is important to keep the acceptable purity levels of conventional plastics when deciding on the appropriate disposal route.

4.4.5.1 Plastic Recycling Facilities (PRF)

Separation facilities specialising in the processing of plastics are known as PRFs (Plastics Recovery Facilities), which typically receive feedstock from Materials Recovery Facilities (MRFs). By handling larger volumes of material they are able to justify higher technology sorting methods for a wider range of polymer types.

Automated stations may be used to target all or a wide selection of plastics that can be identified and separated by polymer type. Manual sorters are restricted to targeting plastic types that can be distinguished visually.

WRAP (2009) illustrate the economic conditions encountered where mixed plastic streams are processed in an MRF and subsequently at a PRF. This presents a higher cost of separation than where a bottle-only plastic fraction is processed.

[32] Based on data collected by WRAP for 'Review of Biodegradability of BS EN 13432 Certified Bags in AD and IVC Systems' 2010.

Biopolymer applications, as with conventional polymers, extend beyond bottles alone, and accurate data would help to establish scale issues related to the economic justification of facilities. Since actual values of recovered bioplastics for reprocessing are unknown (and awaiting the development of suitable reprocessing routes), the information for conventional plastics are described to set the scene below. Some of the PRF data is not directly applicable because the economic case is built up around co-location of PRF and reprocessor facilities[33].

4.4.5.2 Economic & Throughput Requirements for MRFs and PRFs

When an MRF operates in a semiautomatic mode with a throughput of 7 tonnes/hr, depending on the composition of input material, it is feasible that no gate fee is required to support the operation. In this mode, plastic film is removed early in the process and all rigid plastics are removed using a single Near Infra-Red (NIR) sort station to be baled and sent to a PRF as a mixed product (one further NIR sort unit targeting PET may be justified at this scale)[34]. When the scale rises beyond 20 tonnes/hr, separate sort stations for PET and HDPE products become justified.

A fully manual MRF requires a subsidy of £9/tonne (minimum) of commingled feed (dry recyclables) to be viable. This translates to a gate fee of £120 for every tonne of plastic if the MRF were operated commercially. Such an MRF derives little benefit from increases in scale. A stand-alone PRF requires a capacity of greater than 80k tonnes /annum to be viable. The scale may be reduced if the mixed rigid plastics feed (which includes PET and HDPE) can be obtained for under £70/tonne. In automated options for the MRF and PRF analysis, the economics are found to be more sensitive to yield and selling price than to labour or utility costs (WRAP 2009).

4.4.5.3 The Integration of Bioplastics into the Current Infrastructure

With PLA bottles entering the MRF/PRF disposal route, NIR technology sorting could place it in the most appropriate stream. For example, in a semiautomatic MRF the PLA could be targeted with the rigid plastics and be sent for further processing or remain in the reject stream and passed on to residue. Additional costs would be incurred if neither of these destinations were suitable. The PLA may then need to be specifically picked from the MRF residue line or allowed to pass through the PRF to the PRF residue. In the latter case the cost impact would be due to net capacity reductions in the PRF. A viable reprocessing route that could justify a dedicated PLA sort unit in the PRF would obviate this latter issue.

If NIR methods are employed with PLA present in the feed, polymer streams such as HDPE, PP and PET can keep an acceptable purity suitable for reprocessing; though existing facilities may be forced to invest in modifying their systems to meet product specifications. If a wider range of polymers is considered, including various

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[33] It is important to review the specific conditions used for the analysis in WRAP's (2009) report prior to using the information. A number of cost and sale price assumptions contribute to these results.

[34] For collections using a two-stream approach (i.e. paper collected separately) then the MRF can remove the film automatically from containers and separate the plastic using NIR technology.

bioplastics, the picture is less clear as the suitability and performance of NIR techniques for new bioplastics, other than PLA, is not understood well enough on commercial scale equipment. However, conventional plastics from renewable sources will be channelled along existing reprocessing routes without a deleterious impact on separation methods or the products.

The hazards to other recycling streams also needs to be assessed taking into account biopolymer abundance, the impact of any hazard and the efficiency and cost of measures that can be taken to prevent such impacts. The methods to protect other materials should be determined in advance of development and exploitation[35]. Again only PLA has been studied here. If it contaminates PET for reprocessing, it can cause operational and product quality problems. COTREP (2007) found that PLA can be removed by NIR from polymer streams either as a target material or by positively sorting the required fractions. Tests with 2% and 5% PLA in PET caused problems in the drying equipment as it agglomerated and adhered to the dryer walls.

In a bottle to bottle study with 2% PLA, no viscosity build up issues were observed following condensation polymerisation. Concentrations of 0.01%, 0.1%, 0.3%, 2.5% and 5% PLA in PET were used to prepare slabs for examination. The 0.01% sample was acceptable but opacity was observable for the 0.1% sample and there was significant yellowing in the sample containing 0.3% and above. A bottle to fibre study incorporating 0%, 1%, 2.5% and 5% of PLA in the feed indicated that no problems were encountered (COTREP 2007a and b).

A detailed study of PLA inclusion in PET is also presented by Natureworks (2009) where the PET product following NIR sorting (positively sorting PET) resulted in a PLA contamination level of 453ppm (0.045%). Plaques (453ppm PLA) and sheets (net 0.03% PLA) were fabricated and no differences were observed between test and control materials, and no dryer operation issues were detected. On the other hand if PET recycling industry sources are cited (van Keyenberg 2006), PLA contamination of PET needs to be kept below 10-20ppm (0.001-0.002%). This is similar to the requirement for PVC although this is challenging to achieve, so in principle, is attainable, but PLA presents different process challenges.

Assigning costs and impacts incurred to current recycling routes can only be investigated when information is available for the separation and purification options. Using the PLA recycling issue as an example, the following points should be considered: additional processing costs, cost impact of any other processing problems, any critical levels of PLA which trigger further measures and the critical level of PLA in the waste stream that represents a recovery business opportunity. If this method is suitable for the identification of all proposed biopolymers, the future configurations for MRF, PRF and reprocessors to respond to biopolymer development will become clearer.

[35] Eg. PLA contaminates PET for reprocessing as it can cause operational and product quality problems.

4.5 Environmental Review

Based on the research presented above, the Consortium, through discussions with Defra, selected the following seven bioplastics/applications for detailed environmental review and the focus of the remainder of the project:

- PLA multilayer film from Natureworks
- PLA durable goods
- Starch food waste bag from Novamont
- Cellulose film from Innovia
- Starch agricultural mulch from Novamont
- Renewable PET bottle from the Coca-Cola Company
- PHA casings

The justification for this selection was based on each entity's market profile, access to data and its end of life scenario. Additionally, Defra specified that a good mix of bioplastics and applications should be taken forward. Each chosen entity, its justification and key market information is provided in Figure 10.

Figure 10 Bioplastic/Application Summary and Justification Table

	PLA Film - Multi-layer	PLA Laptop Cover	Starch Food Waste Bag	Cellulose Film	Renewable PET Bottle	Starch Mulch Film	PHA
Trade Names	Ingeo	Not available	Mater-bi	Natureflex, Acetate, CAB, Rayon, Cellophane	PlantBottle	Mater-bi	Biopol, Nodax, Mirrel
Manufacturers	Natureworks	Used by Sony and Fujitsu	Novamont	Innovia, Clarifoil	The Coca-Cola Company (USA)	Novamont	Metabolix, Meredian,-Kaneka, Tianjing-DSM, Tianan China
Feedstock	Corn starch	Corn starch	Starch-based	Wood pulp	Petrochemical derived terephthalic acid and bio-based ethylene glycol	Starch-based	Polyester produced bacterial cells, (PHBV made from corn)
Renewable Biomass Component	100%	100%	up to 100%	100%	30%	up to 100%	100%
Compostibility	Meets EN13432	Meets EN13432	Meets EN13432	Meets EN13432	Does not meet EN13432	Meets EN13432	Meets EN13432
Market profile - Current worldwide production	100,000 tonnes total PLA	100,000 tonnes total PLA	60,000 tonnes total starch-based	30,000 tonnes from Innovia but 800,000 tonnes worldwise production.	50,000 tonnes recycled PET equivalent of nearly 2 billion 20-ounce Coca-Cola bottles	60,000 tonnes total starch-based. (Ag plastics total UK production approx 44k tonnes, mulch represents around 5k tonnes of this)	90,000 tonnes
Market profile - Current worldwide production capacity	155,000 tonnes total PLA	155,000 tonnes total PLA	240,000 tonnes (Including blends with biodegradable polyesters that may be bio- or petro-based.)	1 million tonnes	100,000 tonnes	240,000 tonnes (Including blends with biodegradable polyesters that may be bio- or petro-based.)	<50,000 tonnes
Justification for Selection	Natureworks is the largest manufacturer of bio-based plastic and this film has potential to displace a significant conventional plastic tonnage	A non-packaging and durable product to extend the coverage of the project	Opportunity to investigate the AD possibilities	Desire to cover key UK manufacturers and all major starting raw materials, potential to displace significant conventional plastics tonnage	If successful it could substitute a large tonnage of material. Coca-Cola trial in USA	Non-packaging use and agricultural plastics are a key use of plastics	2nd/3rd generation bio-based plastic - likely to be widely used in the coming years

The seven bioplastics/applications selected for in-depth environmental review were investigated using desk-based research and some stakeholder consultation. This research was used to identify the environmental impacts of each entity, which are summarised in this section of the report. Additionally, each environmental study was critiqued by the project team to assess its compliance with the ISO 14040 series and robustness of the data.

A total of 10 LCAs and six environmental summaries were found to relate to one of the entities selected for detailed review. The key results arising from this assessment are detailed by bioplastic/application below.

4.5.1 PLA Film

- Three LCA studies were found to relate to PLA film. Two were cradle to gate analyses considering the production of the Ingeo™ pellet (Vink et al 2003 and 2007) and a further study was a full LCA of a PLA multi-layer film (Vidal 2007).
- Up to pellet production, lower energy and water use was seen for PLA than conventional plastics. An improvement in these differences was seen between the 2003 and 2007 studies.
- For the multi-layer film, lower GWP and fossil fuel depletion were seen for the biopolymer compared to conventional plastic film. Eutrophication impacts were higher for the PLA.
- An LCA of a PLA multi-layered film (composed of PLA and PVOH for use in packaging fresh fruit and vegetables) was carried out by Valpak Consulting to supplement this information.

4.5.2 PLA Durable Goods

- No studies were found to relate to automotive parts or cell-phone cases, although these products are relatively widely used.
- One study was found to cover a Fujitsu PLA laptop cover (Kimura and Horikoshi, 2005) and identified this as producing 15% fewer CO_2 emissions when combusted compared to a conventional plastic cover. If recycled the PLA cover was shown to reduce CO_2 emissions by 29%. This study was not considered robust by the project team.

4.5.3 Starch Bag

- Three LCAs and four environmental summaries covering the impacts of starch bags were reviewed (Morken & Nyland 2002, Estermann and Schwarzwalder 1998, Estermann 1998, James and Grant 2002, Ademe 2002, Imperial College 2007 and Mohee et al 2007).

- In general, although there were variations between all of the LCA studies, an apparent trend is that bio-based polymers do offer some environmental benefits, including the reduction in use of fossil energy resources and reduced greenhouse gas emissions when the optimal waste management options are used.

- The dominant source of environmental impacts associated with biodegradable bags appears to be the extraction and production of the base raw materials.

- Landfilling of biopolymer based bags emerged as a less favourable waste management option due to the release of methane from anaerobic degradation. Incineration with EfW was the disposal option which resulted in the lowest environmental impact for the single use biopolymer based bags.

- The fossil fuel polymer based bags have higher resource impacts (abiotic depletion).

- Global warming potential was higher when starch bags were used to collect waste that is destined for landfill.

4.5.4 Starch Mulch Film

- No studies specifically covering mulch applications of Mater-Bi® material were found.

- An LCA completed by Novamont and Valpak Consulting was carried out for use by the bioplastic manufacturer and Defra.

4.5.5 Cellulose Film

- One environmental summary produced by Innovia (2007) was found, but this provided only comparative data and no absolute values and referred to a cradle to gate analysis.
- An LCA carried out by Innovia and Valpak Consulting was used to supplement this information for use by the bioplastic manufacturer and Defra.

4.5.6 Renewable PET bottle

- One full LCA has been conducted but it is not in the public domain. There is only some summary data on carbon emissions available indicating 25% fewer emissions compared to conventional PET bottles (Coca-Cola Company 2009).

4.5.7 PHA

- Three LCA studies for PHB were reviewed as part of this study. PHB is a type of PHA (PHA is a class of polymer - there are 150 PHA polymers with slightly different structures). PHB is one of the most common ones and as such the results of these studies are seen as indicative. Two studies considered a cradle to gate analysis (Harding 2007 and Kim and Dale 2008) and a further study was a full LCA considering a CRT monitor housing and automotive panels (Pietrini 2007).
- When considered from cradle to gate, PHB is seen as having reduced GHG emissions and non-renewable energy consumption when new technology is considered.
- One study found a GHG credit to be produced as a result of energy recovery within the fermentation process (Kim and Dale 2008).
- On a cradle to grave basis, the chosen application and its conventional plastic equivalent appears to be significant in determining environmental benefits, with the CRT monitor housing being superior to its conventional alternative which was high impact polystyrene (HIPS), whereas the automotive part was not based on it being compared to a PP-based panel.

4.6 Policy & Legislative Review

This section of the report aims to provide an overview of the current policy and legislative initiatives that support the use of bioplastics in the EU, USA and UK. The aim of this review is to highlight concepts that might be relevant for the development of a UK framework. The majority of these policy initiatives can be categorised into four key areas of impact; sustainable practices; production of biomass; packaging materials and waste disposal.

Legislation and commitments to reduce greenhouse gases (GHG) were key features of sustainability polices whilst legislation promoting the reduction, reuse and recycling were key for packaging materials. Measures to promote biomass production encouraged farm diversification, and legislation on disposal of bio-wastes impacted waste disposal practices. Some of these specific key initiatives are now summarised.

4.6.1 Lead Market Initiative

The European Commission's Lead Market Initiative aims to facilitate the early adoption of innovative technologies. The initiative recognises that market entry for new technologies is difficult, however if barriers can be lowered it becomes possible to build early markets of sufficient scale that help to justify investments. In 2009 an Ad-hoc Advisory Group for Bio-based Products published a report on the measures that could be used to promote bio-based materials. The Advisory Group used the European Commission's Lead Market Initiative[36] as a framework. This report summarised a number of policy and legislative actions that would be of benefit to the bio-based industry. The executive summary includes 6 recommendations; 1) legislation promoting market development; 2) product specific legislation; 3) legislation relating to biomass; 4) green public procurement; 5) standards and certification and 6) financing & funding of research.

The first recommendation of this report is that there should be greater and stronger legislation in place that promotes market development. Bioplastics may provide better greenhouse gas performance compared to traditional plastics made from petroleum feedstocks, depending on their whole life cycle assessment. The EU promotes sustainable development with a series of strategies that cover the expansion of usage of renewable resources and the reduction in non-renewable resource consumption.

In July 2010, The European Commission published “Europe 2020”. In this report the EU reinforces these priorities outlining a plan that will focus on developing an economy based on knowledge and innovation, which will promote a more resource efficient, greener and more competitive economy. A critical factor in these plans is the achievement of climate and energy targets with reductions in GHG emissions, so

[36] http://ec.europa.eu/enterprise/policies/innovation/policy/lead-market-initiative/

the development of a scheme that promotes or recognises the carbon savings of bioplastics is considered important.

4.6.2 German Packaging Ordinance

In Germany, packaging legislation is dealt with through the German Packaging Ordinance. Under these regulations businesses are required to submit annual declarations detailing packaging placed onto the German market, have agreements with licensed collection and disposal systems and ensure take-back of all packaging. Within these regulations there is support for packaging made from biodegradable materials. If all the components are compostable and independently certified to the appropriate test standards, the manufacturers do not have to pay the license fees imposed by the packaging recycling systems. However, the producers and distributors of this packaging still have to ensure that a maximum fraction of these materials is being recycled.

Similarly if producers and distributors participate in collection systems and have packaging that has a renewable raw material content of 75% or more, which is also biodegradable, they can be excluded from the mandatory deposit scheme operated in Germany for one-way beverage packaging.

Additionally, Germany operates a BioWaste Ordinance. This separates at source organic residues from households, gardens and parks and is a cornerstone of their waste management. The Biowaste Ordinance (BioAbfV) of 1998 covers the application of treated and untreated bio-wastes and mixtures on land which is used for agricultural, silvicultural and horticultural purposes. It also covers suitable raw materials, quality and hygiene requirements, and treatment and investigations of such bio-wastes and mixtures. In this Ordinance biodegradable plastics are defined as renewable raw materials with proven degradability by testing to an appropriate standard that is approved for composting.

4.6.3 Taxation Benefits

Taxation benefits are seen as an important policy tool in the promotion of bioplastics in a range of applications. Such credits already exist in Germany, Italy and Belgium and more are on the way in France[37]. Therefore, the playing field is not level across the EU member states. The initiative provides a production tax credit for bioplastics with the intention to encourage investment, production, and adoption of these materials in a developing market. For example, in Italy biodegradable mulch films are subject to a 16% reduction in VAT compared to conventional films.

Figure 11 is a summary of taxation types and levels for The Netherlands, Latvia, Romania and Belgium, which have been selected based on the availability of tariff

[37] https://ktn.innovateuk.org/web/polymers/articles/-/blogs/some-key-findings-from-our-bio-plastics-for-packaging-event-with-the-west-midlands-rfa;jsessionid=2E66846CA0F18F4762681A447D27971D.9OphEwv4

information. The majority of those below have adopted a scheme with lower tariffs for biobased materials such as wood, paper and bioplastics.

Figure 11 **Taxation by Country**

Country	Tax Type	Units	Tariff
Netherlands	Packaging	€ per kg	Plastic = 0.4705 Bio Plastic = 0.079502
Latvia	Natural Resources	€ per kg	Plastics= 0.92 Bio Plastics = 0.21
Romania	Tax on bags	€ Per bag	0.04
Belgium	Eco tax	€ per kg	Exception saving €3/kg

Direct intervention against existing petrochemically derived products has also been used as an incentive for bioplastics. A number of countries have banned the use of conventional but not bioplastic carrier bags. In 2002, the Irish government passed a tax on plastic bags, which resulted in a 94% reduction. Similar approaches have been used in other countries with varying success. The Irish success could be attributed to the steep tax at 33 cents per bag and the fact that plastic bags were not manufactured in Ireland. Therefore, there were no strong political or economic arguments that hampered its implementation.

Similarly in 2007 an Italian Finance Act included a provision for a tax on conventional plastic carrier bags and a €0.01 tax on conventional plastic bottles for mineral or table water, which provides an opportunity for bioplastics. Italy now plans to ban the production and distribution of non-biodegradable plastic bags.

In Belgium the direct tax approach was less successful. The Belgian Government tried to introduce a carbon-based tax on all packaging materials in 2007 but backed down in the face of strong opposition from a coalition of environmentalists, industrialists and consumers. In an amended scheme the tax on all packaging materials was dropped to be replaced by a tax on selected types of packaging such as plastic carrier bags (€ 3 per kg) and plastic films (€ 2.70 per kg).

In France, the Government proposed a series of laws that would promote the use of bioplastic bags. It stipulated that all rubbish disposal bags had to have a 40% bio-based content and that by 2010 all non-biodegradable bags would be banned. This was not successful. The European Commission ruled that this would be against free trade and was therefore anti-competitive. France is now working on transforming these measures into an incentive based ‘ecotax’ approach.

4.6.4 BioPreferred Programme

European member states have given political support to an increase in Green Public Procurement (GPP). The improvements have to be accomplished at the level of member states. In the USA, a voluntary labelling and procurement program, The USDA BioPreferred[38] Programme, arose from the 2002 Farm Bill. It seeks to increase the take-up, purchase and use of renewable, environmentally friendly bio-based products, whilst providing "green" jobs and new markets for farmers, manufacturers, and retailers. The programme has demonstrated a number of successes in bioplastics. This approach has resulted in further legislation and the USA is leading the development of biofuels, with a new legislation bill that encourages consumers to switch.

4.6.5 Courtauld Commitment

In the UK, an approach being adopted by the grocery sector is called the Courtauld Commitment. The Commitment encourages the grocery retail industry to adopt a series of indicative or binding targets that are linked to the reduction in the environmental impacts of packaging products.

The Courtauld Commitment is a voluntary agreement aimed at improving resource efficiency and reducing carbon emissions. The Courtauld Commitment Phase 1 commenced in 2005 with an aim to look at new solutions and technologies so that less food, products and packaging ended up as household waste. This has moved on to the Courtauld Commitment Phase 2 which was launched on 4th March 2010. The new approach adopted in Phase 2 moves away from solely weight-based targets and aims to achieve more sustainable use of resources over the entire lifecycle of products, throughout the whole supply chain. Specifically its targets are**:**

- Packaging – to reduce the weight, increase recycling rates and increase the recycled content of all grocery packaging, as appropriate. Through these measures the aim is to reduce the carbon impact of this grocery packaging by 10%.

- Household food and waste – to reduce UK household food and drink waste by 4%.

[38] http://www.biopreferred.gov/?SMSESSION=NO

- Supply chain product and packaging waste – to reduce traditional grocery product and packaging waste in the grocery supply chain by 5% - including both solid and liquid wastes.

This commitment is supported by a total of 29 major retailers and brand owners. Engagement with supporters of this agreement may be beneficial for the bioplastic industry as there might be opportunities to promote the benefits these materials offer in lower GHG emissions.

4.5.6 Renewable energy policies

The renewable energy sector in the UK is established and could help provide some benchmarks for policy and legislation within the bioplastics sector. The energy sector has utilised a combination of policies to reduce the impacts throughout the supply chain. Incentive tariffs that guarantee price, government purchasing schemes that act as incentives to industry, sales tax rebates and consumer grants or rebates are just some of the polices and measures adopted by this sector.

The most successful of these initiatives have been the ones that have helped to reduce uncertainty in a developing market e.g. long term contracts with guaranteed unit returns for set prices. Inconsistencies in policies were seen as a major problem of regulation especially if a set of measures had different impacts in the same market place.

In the renewable energy sector legislation was seen to help provide the catalyst for change in a developing market. However, it was recognised that it was vital that the correct policies were adopted and that inconsistencies were avoided.

4.7 Assessment of Barriers and Opportunities for Use

A multi-criteria assessment software package (V.I.S.A)[39] was used to aid the decision making process in identifying barriers and opportunities in bioplastics researched as part of this project. This software was used to compare each bioplastic with a corresponding conventional plastic application in relation to each defined criterion. Seven comparison scenarios were created in the assessment tool for the modelling and analysis, based on available data and LCAs, as shown in Figure 12 below.

Figure 12 Comparison Scenarios

Scenarios	Bioplastic	Conventional Plastic
1	PLA multi-layered film	PP rigid / film
2	Cellulose film	PP film
3	Starch mulch	LLDPE mulch film
4	Starch bag	HDPE bag
5	PHA casing	Polycarbonate casing
6	PLA laptop casing	Polycarbonate casing
7	Renewable PET bottle	PET bottle

The criteria and sub-criteria used to evaluate the plastics were decided upon based on discussions with the project Steering Committee and through stakeholder engagement, although they were partially limited by the data available. The criteria used were:

- Environmental – GHG emissions, land use, non-renewable resource use
- Economic – resin costs, sales value
- Technological – fit with the current waste management system, production capacity
- Legislative – incentives, penalties
- Social – job creation

4.7.1 Criteria, Sub-criteria and Assumptions

The data inputted into the multi-criteria tool was based on information gathered and agreed by the partners involved in the project. However, where there was lack of accurate data, some assumptions had to be made. Since it is important to understand the background information on the sub criteria used in the model, an explanation is given together with any assumptions made.

[39] http://www.visadecisions.com/

4.7.1.1 Environmental: GHG Emissions

GHG emissions relate to those gases contributing to the greenhouse effect. Those relating to the life cycle of the materials analysed are aggregated according to their impact on radiative warming compared to carbon dioxide as the reference. Therefore, impacts are expressed in kg CO_2 equivalents. The methodology uses climate change factors with a timeframe of 100 years, providing an output in carbon dioxide equivalent (CO_2e) emissions.

Where available, the data used in the model is based on the full life cycle of the material and product under investigation, taking what is considered to be the current waste management scenario. However, in some cases this was not possible and data referring to the cradle to gate portion of the life cycle only was available. Where comparisons between two materials are made, data considering the same life cycle stages is used only.

The data used in the model is based on a functional unit of 1kg of material; however, it should be noted that in some cases the product in question may require more or less material to meet the same functionality as its comparative conventional plastic. In such cases, an alternative figure was also modelled based on the required functional unit to perform the selected application.

The data used within the model was collected from the following sources, some of which remain confidential, and as such, raw data cannot be included within this report:

- PLA multi-layered film – cradle to grave data taken from Valpak Consulting (2010a)
- Cellulose film - cradle to grave data taken from Valpak Consulting (2010b)
- Starch mulch – cradle to grave data taken from Novamont (2010)
- Starch bag – cradle to grave based on data published by NNFCC (2008)
- PHA – cradle to gate based on that published by Kim and Dale (2008)
- PLA laptop cover - cradle to gate data taken from Valpak Consulting (2010a)
- Renewable PET bottle – cradle to gate data based on 25% reduction in emissions from conventional PET bottle, based on claims from Coca-Cola (2009)
- PET bottle – cradle to gate data based on Plastics Europe information

- PP film - cradle to grave data taken from Valpak Consulting (2010b)
- PP - cradle to gate data taken from Plastics Europe
- LLDPE mulch film - cradle to grave data taken from Valpak Consulting (2010c)
- HDPE bag – cradle to grave data based on data published by NNFCC (2008)
- Polycarbonate casing – cradle to gate data based on Plastics Europe information

4.7.1.2 Environmental: Land Use

The amount of land required to produce 1kg of each bioplastic has also been accounted for in the model. This is based on the m^2 required to produce 1kg of polymer and does not account for the varying ecological value of the land. This information has been collected from the following sources:

- PLA – provided by Natureworks
- Cellulose –provided by Innovia Films
- Starch – provided by Novamont
- PHA – unavailable in the literature and from the manufacturers. Based on 10 tonnes of sugar being produced per hectare and 3 kg of sugar being needed for 1kg of PHA, therefore, $3m^2$ is required (Omar et al, 2001).
- Renewable PET - unavailable in literature and from manufacturer. Based on 1 hectare of sugar cane giving 3.1 tonnes of ethanol (ethanol to ethylene glycol is a conversion of 1.12), 3.47 tonnes of ethylene glycol is produced from 1 ha land or 2.89 m^2 per kg of material. Plant bottle is 30% plant matter by weight and therefore 0.867 m^2 per kg (Rosa, 2005, Braskem 2010 and Shell, 2010).

A consideration of the potential to use food crop land is also made in qualitative terms, as this is linked to any assessment of land use.

4.7.1.3 Environmental: Non-Renewable Resource Use

This impact category is also derived from LCA-based studies and accounts for the primary non-renewable energy used within the system and is measured in MJ. This parameter was not always available and, as above, varied from cradle to grave and cradle to gate.

Where used, the data was sourced from:

- PLA multi-layered film – cradle to grave data taken from Valpak Consulting (2010a)
- Cellulose film - cradle to grave data taken from Valpak Consulting (2010b)
- Starch mulch – cradle to grave data taken from Novamont (2010)
- Starch bag – not available
- PHA – cradle to gate based on data published by Kim and Dale (2008)
- PLA laptop cover - cradle to gate data taken from Valpak Consulting (2010a)
- Renewable PET bottle – not available
- PET bottle – not modelled as starch equivalent unavailable
- PP film - cradle to grave data taken from Valpak Consulting (2010b)
- PP - cradle to gate data taken from PlasticsEurope.
- LLDPE mulch film - cradle to grave data taken from Valpak Consulting (2010c)
- HDPE bag – not modelled as starch equivalent unavailable
- Polycarbonate casing – cradle to gate data based on Plastics Europe information

4.7.1.4 Economic: Resin Cost

This cost relates to that of the production of 1 kg of resin in USD. This is deemed to be a suitable measure to account for the manufacturing costs but also the additional research and development costs required for the bioplastics market. These vary significantly by production capacity and as such could not be assessed as independent criteria. This was included in addition to the sales value detailed below, as the price can be influential at any point in the supply chain, not just at the point of sale of the finished item. The data has been gathered from the following sources:

- PLA multi-layered film – based on information collected from Sales Conferences during 2009 and further discussions with suppliers and users in 2010

- Cellulose film – price only for pulp and not for resin, as no resin is used in the manufacture of the films. This was provided by Innovia Films.
- Starch mulch – based on information collected from Sales Conferences during 2009 and further discussions with suppliers and users in 2010
- Starch bag – based on information collected from Sales Conferences during 2009 and further discussions with suppliers and users in 2010
- PHA – based on information collected from Sales Conferences during 2009 and further discussions with suppliers and users in 2010
- PLA laptop cover - based on information collected from Sales Conferences during 2009 and further discussions with suppliers and users in 2010
- Renewable PET bottle – not available
- PET – not modelled as renewable PET data not available
- PP - London Stock Exchange (22 June 2010)
- LLDPE – London Stock Exchange (22 June 2010)
- HDPE – London Stock Exchange (22 June 2010)
- Polycarbonate – London Stock Exchange (22 June 2010)

4.7.1.5 Economic: Sales Value

This sub criterion was based on the retail value of 1kg of the material used in each application assessed. The data was sourced from the following:

- PLA multi-layered film – based on information collected from Sales Conferences during 2009 and further discussions with suppliers and users in 2010
- Cellulose film – provided by Innovia Films
- Starch mulch – based on information collected from Sales Conferences during 2009 and further discussions with suppliers and users in 2010
- Starch bag – based on information collected from Sales Conferences during 2009 and further discussions with suppliers and users in 2010

- PHA – not available
- PLA laptop cover - based on information collected from Sales Conferences during 2009 and further discussions with suppliers and users in 2010
- Renewable PET bottle – not available
- PET bottle – not modelled as renewable PET data not available
- PP - London Stock Exchange (22 June 2010)
- LLDPE – London Stock Exchange (22 June 2010)
- HDPE – London Stock Exchange (22 June 2010)
- Polycarbonate – London Stock Exchange (22 June 2010)

4.7.1.6 Technological: Fit with Current Waste Management System

This sub criterion was based on a scoring system relating to the suitability of current waste management practices to accept and process the materials reviewed, and does not make an assessment of the environmental impacts of various end of life options. There is a wide variety of collection and recycling schemes adopted through the UK, and each will have been selected to respond to the waste type, composition and local practical and political preferences. The approach adopted was to mark the material as if processed by an appropriate scheme that would be established within the UK.

The assessment was split into three separate scenarios to indicate the impact of each material, depending on where it was routed. The categories assessed were:

- Fit with landfill, incineration or EfW
- Fit with recycling system
- Fit with composting or AD

Each scenario was then considered based on three aspects of the waste management infrastructure in the UK:

- Infrastructure availability
- To what extent the impact on other materials/recyclables is benign
- Process adaptations required to deal with the material

4.7.1.7 Technological: Production Capacity

This relates to the global production capacity of each bioplastic and application in tonnes. The bioplastic data has been gathered from the Consortium's knowledge of the market and through conversations with manufacturers. Data referring to conventional polymers was sourced from Plastics Europe (2009) and Innovia Films.

4.7.1.8 Legislative: Incentives & Penalties

This information was gathered based on the Consortium's knowledge of the bioplastics industry. No legislative incentives were considered applicable for any bio or conventional plastics, and only starch mulch was found to be eligible for legal penalties in relation to the current requirement for it to be removed from the land after use.

4.7.1.9 Social: Job Creation

Though it is very difficult to accurately predict the level of job creation, a number of estimates have been attempted by Institute for Prospective Technology Studies. The institute estimates that the overall global creation of jobs will balance out any losses in the production and manufacturing industries, and so the only job creation observed will be in the agricultural sector. The researchers predict this increase to be modest, with only a maximum of 3000 jobs being created in the EU by 2020; this figure was based on the assumption that all the plastics were produced from wheat starch from within the EU (M. Crank, et al., 2005).

The bioplastic market is global and these bioplastics are not solely produced from wheat grown within the EU. Other crops used in the production of bioplastics are more energy and labour intensive as well as being grown using alternative farming practices. The following estimates are based on current global employment practices and have been extrapolated for the level of bioplastic forecast to have been produced by 2020 (M. Crank, et al., 2005, L. Shen, et al., 2010). This is with the exception of the bio-PET bottle, which was calculated from the amount of ethylene glycol currently produced for the bio-PET bottle with a growth of 7% per year to 2020 (Gerson Lehrman Group, 2010). The number of workers needed to produce the crop has been estimated for eucalyptus plantations in Brazil (Veracel Celulose SA, 2010) and sugar plantations in Brazil (Ben Richardson, et al., 2009, The International Labour Organisation, 1994), and the starch is assumed to come from wheat grown within the EU (M. Crank, et al., 2005). It is also assumed that PHA will continue to be grown bacterially using sugar as the main carbon source. However, as discussed in previous sections, this is not necessarily the case. Therefore, it is intended that this data should be taken as a guide only due in part to the number of assumptions, alongside not being able to foresee the increasing mechanization of farming in the developing world. The calculations used are detailed in Figure 13.

Figure 13 Job Creation Calculations

Polymer	Crop	2020 production estimate, tonnes	Hectares	Maximum global job increase

Cellulose film	Trees	90,000	1,200	10
PHA	Sugar cane	400,000	120,000	15,000
Starch	Wheat	1,125,000	225,000	3000
PLA	Wheat	750,000	190,000	2600
PET bottle	Sugar cane	12,000 (of ethylene glycol)	3,500	350

Although it is outwith the scope of this report, a useful indicator for the level of employment that a new production facility may create, can be found in the fact that Dow Chemicals' new Brazil located, £250 million bio-polyethylene factory, which is set to produce 350,000 tonnes of PE per annum, has created 3000 new jobs (R. Pagnamenta, 2008). Within the UK, the Ensus Group has built a £250m bioethanol plant in Wilton, Teesside, which is capable of processing 1 million tonnes of wheat per annum. The estimates for employment from this factory give a fair indication of the job creation potential for any future bioplastic enterprises. The company estimated that the ethanol plant produced 800 temporary construction jobs, has created 100 full time jobs in managing the factory and will help support 1,500 agricultural jobs in the region (Ensus, 2010).

4.7.2 Data Robustness

In order to assess the certainty of any conclusions drawn from this multi-criteria assessment, the robustness of all of the data used was assessed using Defra's 'Five Components of Robust Evidence'. The results of this assessment are detailed in Appendix 1 of this report, and indicate that all the data used is considered to be robust or partially robust.

4.7.3 Results

The results obtained from the multi-criteria tool are detailed in this section by individual comparison. It is important to bear in mind that the results for each of the seven comparisons should not be compared directly with each other and cannot be assumed to represent the conclusions of comparing all bioplastics to conventional plastics.

4.7.3.1 PLA Multilayered Film & PP Rigid/Film

Based on the multi-criteria analysis it is clear that the PLA film offers environmental opportunities through a potential reduction in GHG emissions and use of non-renewable resources and, similar to all of the bioplastics, a potential for job creation through approximately 2,600 posts globally in 2020[40]. Based on the cradle to gate data available, PLA is seen to have around 30% less GHG emissions than the PP per kg of material. Another opportunity not included in the main assessment due to a lack of verified data, is that manufacturers claim the PLA multi-layered film offers shelf-life benefits. As the food contained within such packaging often has much higher GHG emissions than the packaging itself, this represents a further opportunity

[40] As detailed and explained in Figure 13

for the bioplastic. However, this potential benefit does require further research and independent verification.

The barriers identified from the analysis are shown to exist primarily from the economic and technological categories. PLA was shown to be around a third more expensive in terms of both the resin cost and sales value of the material compared to PP film, which is a significant barrier to its uptake. For example, PLA resin is seen to cost around $1.3-1.9 per kg compared to PP which is around $1.2 per kg. However, it should be noted that based on historical data if the price of oil reaches and is sustained at around $85 a barrel then PLA can become cost-competitive with oil-based plastics in the USA.

From a technological perspective there are both barriers and opportunities to using the PLA film in the current waste management system. In terms of being directed to landfill or incineration/EfW, from a technological perspective the bioplastic is not seen as being any different to the conventional alternatives, although under incineration does benefit from biogenic rather than fossilised carbon emissions[41]. If the PLA entered the recycling stream, a barrier is identified for several reasons. Firstly, to identify the film as PLA would require process alterations by separation facilities as it is difficult to identify visually, which would have cost and time implications. Secondly, if the PLA was not segregated it would reduce the quality of the end product if used in significant quantities (studies suggest tolerance levels of anything from 0.001% to 5% contamination (CONTREP, 2007, Natureworks 2009 and van Keyenberg 2006)). Finally, whilst PLA being recyclable is an opportunity, there is no PLA recycling infrastructure in the UK to treat it separately. This compares to the PP rigid or film, which whilst does currently have a very low recycling rate in the UK, is being increasingly collected from households and is recyclable as part of the mixed plastics stream[42].

If the bioplastic were composted or anaerobically digested an opportunity is seen as the conventional alternatives have poor recycling rates and do not have the option of this disposal route, which diverts waste from landfill. However, whilst this opportunity is evident, based on the current waste management infrastructure in place in the UK[43], the volume of material entering these streams is low, UK capacity is also low[44] and there are other potential barriers, such as some AD operator’s fears that conventional plastics will contaminate the process or that pre- or post-processing will be required to allow the bioplastics to break down as required.[45]

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[41] This assessment is based on technological rather than environmental criteria, however it should be noted that under landfill conditions PLA was found to show practically no degradation, similar to conventional plastics (Valpak Consulting 2010a)

[42] Based on the currently proposed changes to the Packaging Regulations with separate targets for plastic bottles and other plastics, this recycling has potential to increase over the next few years.

[43] In 2008-09 only 31% of local authorities offered a food waste collection service (http://www.wrap.org.uk/downloads/Household_food_and_drink_waste_in_the_UK_-_report.e18baddd.8048.pdf)

[44] Currently the UK has 11 AD plants processing approximately 320,000 tonnes of food waste (ENDS Report 426, July 2010), although over the next five years another 600,000 of new capacity is anticipated.

[45] Based on data collected by WRAP for ‘Review of Biodegradability of BS EN 13432 Certified Bags in AD and IVC Systems’ 2010.

A drawback to bioplastics is the use of additional land (around 1.7m^2 per kg in the case of PLA) to produce the feedstock not needed for conventional plastics and this has the potential of being diverted from food crop uses. However, this is not seen as a barrier to their uptake as current land use is not always managed at optimal efficiency and according to the FAO between 250 and 800 million ha of land globally could be brought into production without encroaching upon areas of high ecological or social value (FAO, 2008). Whilst they do put a caution on these figures, based on the projected level of PLA use in 2020 and its land take, this would be only 0.02% of the available land (based on all bioplastic projected capacities in 2020 only 0.1-0.3% of this land is estimated to be utilised.) It should however be noted that this would be a barrier to the use of bioplastics if land is used unsustainably, through converting land that is of high ecological or social value or that would result in a release of a large amount of stored carbon.

As with most of the bioplastics, in terms of UK legislation there is considered to be no penalties or incentives currently available for the use of PLA, however Landfill Directive targets do restrict the total amount of biodegradable municipal waste (BMW) going to landfill in 2020 to 35% of that produced in 1995. The disposal of bioplastics to landfill should therefore be avoided which is a barrier to its use if not disposed of appropriately.

4.7.3.2 Cellulose & PP Film

The analysis revealed that cellulose film offers potential opportunities but also barriers in most of the main criteria assessed. Key opportunities are seen environmentally through a reduction in the use of non-renewable resources, socially through creation of jobs and technologically in the potential for composting/AD.

Similar to PLA, barriers are seen in terms of the pulp costs and sales value of the material being higher (in this case by approximately 25-50%) and from waste management in terms of recycling for the same reasons outlined above for PLA. However, it should be noted that no studies have been carried out to assess the impact of cellulose on the recycling stream and as such this requires further clarification, although based on trials carried out on behalf of WRAP it is known that the material would be considered a contaminant in the film recycling process (WRAP, 2009).

In addition to the above, cellulose has a barrier in terms of the GHG emissions emitted over its life cycle, which are higher than those for an equivalent PP film. Whilst this is a current barrier, the production of all bioplastics suffer from efficiency limitations and are undergoing improvements, which offer the potential to improve their environmental performance; however, without the demand for the material these are likely to be restricted and the improvements required to reduce the GHG emissions to the level emitted from conventional plastics is unknown. Another related opportunity is that the manufacturer Innovia claims that the bioplastic has the ability to improve the shelf-life of fresh foods. As the food contained within such packaging often has much higher GHG emissions than the packaging itself, this represents a further opportunity for the bioplastic, but does require further research and independent assessment.

In terms of land use, once again this is a drawback for the bioplastic, however it is not seen as a barrier due to the large amount of available land identified if used sustainably and without converting ecologically or socially valuable land (as outlined above). Additionally, Innovia claim their product to be made entirely of FSC certified wood, representing the sustainable nature of the feedstock.

4.7.3.3 Starch Mulch Film & LLDPE Film

The use of starch as a mulch film, once again, is shown to offer opportunities in terms of GHG emissions, use of non-renewable resources, waste management and job creation. It was found that three times less starch mulch film was required for use on the same area of land as the LLDPE due to it being thinner, which does partially account for some of the environmental benefits identified. Interestingly, the starch and LLDPE have the same GHG emissions per kg of material manufactured on a cradle to gate basis. However, over the full life cycle the emissions are higher per kg of starch as a result of those generated as the mulch film degrades on the land. Nevertheless, as three times less material is required for the starch mulch compared to the conventional mulch film, overall the GHG emissions are lower.

In contrast to the other bioplastics, starch mulch film offers an opportunity in terms of waste management. The starch mulch film is designed to be left on the land after use and as such does not require removal for waste management, which is likely to be landfill or recycling. Novamont, the manufacturer, claims that is it unlikely to be possible for the starch to be removed after use due to the degradation process commencing[46], and as such would not reach recycling or other waste treatment processes. Whilst the current recycling rate of agricultural films is approximately 20% and likely to increase if the planned Producer Responsibility Regulations on these materials are introduced (Defra, 2009), the LCA used to estimate the GHG emissions of the materials identified that even at a rate of 50% recycling, the bioplastic produced the lower emissions option as it requires three times less material compared to the LLDPE. This is despite the fact that per kg of material the starch end of life GHG emissions are actually higher.

A significant barrier to realising the waste management and environmental opportunity outlined above is identified in the assessment through a current legislative penalty. Currently in the UK, all agricultural films are required to be removed from the land to be disposed of via landfill or recycling. As a result, the mulch film is not able to be used in the UK at present as it cannot be removed from the land based on its degradation. Therefore, this represents a barrier to the use of this film in the UK.

[46] Based on personal dialogue with Novamont 2010

As with PLA and cellulose, starch was found to be more expensive to produce and have a higher selling price than the conventional LLDPE mulch film; in this case being up to approximately twice the price per kg sold. However, as noted above there would actually be less starch used per hectare compared to LLDPE and additionally, no associated removal/ disposal costs. In a recent study on strawberry use in Italy, Piedmont (2010) found the cost per ha of LDPE mulch film to be around €1,500 compared to starch, which was around €1,050. It should be noted that additional transportation costs would be incurred for importing the starch to the UK from Italy. Nevertheless, overall, the starch mulch film is competitive with the conventional mulch, based on sales value.

Production capacity for starch in non-food applications was found to be lower than that of LLDPE and as such is highlighted as a barrier to the use of starch. Whilst in general terms this is true, again it is important to note that less starch is required per hectare and Novamont claims that they have enough production capacity for this product to cover the total mulch film market.

Once again the use of land was seen as a drawback but not a barrier to using starch film, where around 1.9m^2 is required to produce 1kg, which has the potential to be used for food crops. Once again it is important to note that it has been estimated that the potential area of land required for the use of bioplastic production is very small in comparison to the 250 to 800 million ha believed to be available (FAO, 2008).

4.7.3.4 Starch Bag & HDPE/PE Bag

When using starch as a food waste bag it is shown to present opportunities in terms of GHG emissions reductions, being over 20% less than HDPE bags (James and Grant, 2002), waste management with AD/composting options and job creation where around 3,000 jobs are estimated to be created in starch production globally by 2020[47].

In terms of waste management the bags have been seen to have a greater environmental impact if they are landfilled with Morken and Nyland (2002) finding that starch bags to release over two times the GHG emissions of a PE equivalent bag under these conditions, however in terms of the technological implications, this route is not affected by using a bioplastic. In terms of recycling the starch bag, similar to the other bioplastics, this has potential to cause contamination. Nevertheless, it is designed to be part of a structured food waste disposal programme and as such should be routed to the appropriate composting/AD facility, which represents an opportunity. However, once again these services to households are restricted[48] and some AD operators have been shown to have concerns about

[47] As detailed and explained in Figure 13

[48] In 2008-09 only 31% of local authorities offered a food waste collection service (http://www.wrap.org.uk/downloads/Household_food_and_drink_waste_in_the_UK_-_report.e18baddd.8048.pdf)

the use of these food bags[49], which currently does represent a barrier to this potential management. Additionally, there is potential for these bags to be collected for recycling with conventional polyethylene bags and as such contaminate the recycling process, which once again is seen as a barrier.

Economic barriers to the use of starch bags are identified through higher resin costs and sale prices of up to four times that of conventional bags, with starch resin being around $1.6-4 per kg compared to HDPE which is around $1 per kg. This is partially related to the lower production capacities identified for the starch compared to HDPE bags, where starch (in non-food applications) is believed to have a global capacity of around 60,000 tonnes, compared to HDPE bags which are estimated to have a capacity of around 7.8 million tonnes50. Environmentally, the land use take, which could potentially be from food crop sources, is also a drawback once again but not seen as a barrier, for the reasons noted above. Finally, as with the other bioplastics Landfill Directive targets restrict the BMW going to landfill which is a barrier for these materials if not managed appropriately.

4.7.3.5 PHA & Polycarbonate Casing

The assessment of PHA and polycarbonate casings for electrical equipment was primarily conducted using cradle to gate data, based on a lack of market information on the specific applications. Based on this, the PHA was found to offer environmental opportunities in terms of lower GHG emissions and use of non-renewable resources. The GHG emissions data reviewed for this study varied depending on which conventional polymer and application it was compared to, but in comparison to a polycarbonate on a cradle to gate basis, polycarbonate was seen to have emissions of 7.6 kg CO_2e per kg (PlasticsEurope, 2010) compared to PHA, which in one study, was found to have a negative carbon footprint of 2.3 kg CO_2e per kg, based on its production process actually generating energy (Kim and Dale, 2008). Based on the same sources, PHA was found to use around 2MJ of non-renewable resources compared to a polycarbonate at 113MJ per kg on a cradle to gate basis, however the authors of this work did assume large amounts of agricultural residues to be used for providing process heat, which could make this comparison unfair.

PHA also has a potential social benefit through job creation. PHA was identified as offering the highest potential global job increase of around 15,000 posts created[51], as its feedstock, sugar cane, and predicted production levels in 2020, create the highest level of agricultural employment among the bioplastics examined.

[49] Based on data collected by WRAP for 'Review of Biodegradability of BS EN 13432 Certified Bags in AD and IVC Systems' 2010.

[50] Based on HDPE bags accounting for around 26% of global HDPE capacity of 30 million tonnes, estimate from http://www.chemsystems.com/reports/search/docs/abstracts/0506_3_abs.pdf

[51] As detailed and explained in Figure 13

Based on the materials being used in electronic applications and the UK waste management infrastructure for waste electricals being recently developed as a result of the Waste Electronic and Electrical Equipment (WEEE) Directive, the material is equally likely to be diverted to recycling whether it is made of the conventional plastic or bioplastic. There is a possibility that the PHA could contaminate the recycling stream; however, as such products require dismantling and pre-treatment it is less likely to cause a problem than in other applications. As a result, this material is considered to neither present an opportunity or barrier in terms of the recycling stream. It also still has the potential to be anaerobically digested or composted after shredding, which offers a further opportunity, although this is currently prevented as a result of the issues discussed above. Polycarbonate can be challenging to recycle and as such there is potential for the PHA to offer environmental savings in this stage of the life cycle. However, further research is required to investigate this potential opportunity.

PHA was found to face an economic barrier based on higher resin costs, being around twice those estimated for the conventional plastics, where PHA resin is seen to cost around $5.8-7.3 per kg compared to polycarbonate at $3.05-3.12 per kg. It is worth bearing in mind that in most applications PHA can be combined with other co-polymers and as such these costs also need to be accounted for.

The land use required for the production of PHA is a drawback compared to conventional polymers, which is estimated to be around $3m^2$ per kg of PHA (Omar et al, 2001 and Page, 1996), and is potentially from food crop sources. Whilst it has the largest area of land required per kg of feedstock of the bioplastics assessed, it still represents only around 0.02% of the land seen as available for agricultural purposes by 2020 based on future production estimates. As a result, land use is not seen as a barrier to its use, if the land is managed sustainably.

4.7.3.6 PLA & Polycarbonate Casing

Comparing the use of PLA to polycarbonate resulted in almost the same assessment of barriers and opportunities as those identified above for PHA. The only difference seen was that relating to the economic assessment, where the PLA was found to offer a slightly lower resin cost and sales value compared to the polycarbonate, where PLA is around $1.3-1.9 per kg of resin and polycarbonate is around $3.05-3.12 per kg. However, it should be noted that PLA durable materials are often composites and the compostability and sales value of the material will be related to the other polymers with which they are combined. Within a typical PLA durable product PLA represents around 30-40% of the material used, with the remaining 60-70% of the material being made of other polymers or additives. Therefore, whilst the costs and GHG emissions of the PLA are seen as lower compared to the polycarbonate, it is the additives and other polymers and their own costs and emissions which will determine if the PLA or polycarbonate are cheaper or have lower GHG emissions; however this will vary widely by the composition/application.

Overall, it is difficult to assess the key barriers and opportunities as they are impacted greatly by the polymers/additives used in conjunction with the PLA.

4.7.3.7 Renewable PET Bottle & PET Bottle

There was only limited information available regarding the PET bottle for the assessment; however certain opportunities and barriers have been identified. Firstly, the renewable bottle is claimed to have 25% fewer GHG emissions than the conventional alternative and as such does offer an environmental benefit. Additionally, the bottle is said to be completely compatible with the current UK recycling processes and as such, based on the criteria, does not have any of the barriers, which are potentially affecting the other bioplastics.

The renewable bottle does have land use as a drawback to its use, being estimated to take around $0.9m^2$ per kg produced (Rosa, 2005), with the potential for its feedstock to have been sourced from food crop land. However, this is not seen as a barrier to its use, as noted above. However, as with the other bioplastics, the production capacity is much lower than the conventional PET bottle, which does represent a barrier to its use.

Whilst no economic data for the renewable PET bottle could be found, through anecdotal evidence it is believed to be more expensive than the conventional bottle in both its production cost and sales value, which therefore does represent another barrier to its uptake.

5 Conclusions

This project has combined a review of published material, stakeholder engagement and primary environmental research to assess the current and emerging bioplastic market. Through multi-criteria assessment based on environmental, economic, technological, legislative and social information, the areas of opportunity and barriers to using various key bioplastics have been identified. Where barriers have been found, the report goes on to make recommendations as to how these can be overcome.

5.1 The Bioplastic Market

The research conducted has identified 12 broad categories of bioplastics currently available on the market or in development. These categories are:

- Poly Lactide (PLA)
- Poly (3-Hydroxy Alkanoate)s (PHA)
- Polytrimethylene terephthalate (PTT)
- Bio-Based Polyethylene terephthalate (PET)
- Bio-Based Polyamide
- Bio-Based Polyethylene
- Bio-Based Polyurethane
- Bio-Based Polypropylene
- Polycarbonate (derived from CO_2)
- Starch
- Cellulose
- Lignin

It is estimated that the current worldwide production of bioplastics is around 1 million tonnes, with the production capacity estimated to be approximately 1.9 million tonnes. This represents around 0.7% of the global plastics market.

5.2 End of Life Options

Five end of life options for bioplastics were investigated for the project, with the key conclusions made being:

- Landfill - This is an undesirable disposal option due to the release of methane during decomposition under anaerobic conditions for most bioplastics and its place in the waste hierarchy.

- Incineration with EfW - A potentially worthwhile route due to the high GCV of plastics and that bioplastics contain biogenic, rather than fossil-based carbon.

- Composting - Most biopolymers are compostable in industrial installations and/or at home in some situations. This offers the potential for reduced collections and the treatment of food residue without separation. Labelling offers guidance to this, but confusion has resulted over whether biopolymers can be composted at home or in an industrial composting facility.

- AD - This waste treatment offers the advantages of energy production and further diverting waste from landfill. As a new technology AD capacity is currently limited in the UK and some operators have concerns over bioplastic inclusion within their feedstock due to contamination with conventional plastics for example.

- Recycling - Only PLA recycling has been investigated due to this being the only bioplastic which has undergone such trials. The separation and recycling of PLA by NIR separation has been found to be successful but likely to incur additional costs. In order to maintain a good quality conventional plastic stream, various acceptable PLA limits have been identified in different studies: these ranged from 0.001% to 5%.

5.3 Policy Review

- **Legislation**: No one policy measure will help develop the market. A series of initiatives need to be considered. These initiatives must impact the entire supply chain. Government purchasing schemes can act as incentives to industry to make investment decisions. Other mechanisms, such as guaranteed pricing helps to remove any uncertainty in the market place. However, it is important to avoid complicated schemes as this can lead to confusion.

- **Industrial cooperation**: The bioplastic industry needs to cooperate and collaborate to ensure that inconsistencies in approaches are avoided.

- **Financial support**: Grants can help support investment decisions, however revenue support is better for promoting commercial success.

- **Creating awareness**: Measures that help develop consumer awareness need to be considered. Brand owners are also key to creating awareness and can help develop the markets for bioplastics.

5.4 Barriers to Bioplastic Uptake

This study has identified a series of barriers which currently prevent the bioplastics investigated from occupying a larger share of the market. These are:

- **Resin costs and sales value**: the bioplastics under investigation were found to be more expensive to produce and retail than conventional alternatives. This ranged from cellulose and PLA being up to 50% more expensive, to starch and PHA reaching up to four times the price of conventional plastics. When used in durable applications, PLA was seen to offer an economic advantage over polycarbonate. However, this is likely to only be around 40% of the material used and the comparative costs of additives/ polymers are not accounted for. It should be noted that as production efficiencies and economies of scale increase, the costs of bioplastics are anticipated to decline.

- **Diversion to AD/composting**: current potential opportunities in waste management through the use of composting and anaerobic digestion techniques cannot be fully realised due to; a lack of collection infrastructure; limited UK capacity; householder confusion in identifying bioplastics and concerns from some AD facility operators over conventional plastic contamination and process changes required to attain the required bioplastic degradation.

- **Contamination of recycling streams**: where bioplastics are used in formats that are currently recycled in the UK, they tend to be treated as contaminants, and have the potential to reduce the quality of the end product (various acceptable PLA limits have been identified in different studies: these ranged from 0.001% to 5%). It should be noted that bioplastics such as PLA can be positively identified and separated prior to reprocessing, but this would incur cost and time implications. Additionally, many of the packaging formats assessed, such as films or rigid non-bottle plastics, currently have recycling rates of only around 3% in the UK (Valpak Consulting, 2009); however, these levels are increasing.

- **Production capacity**: bioplastics currently represent around 0.7% of the plastics market, with a global production capacity of around 1.9 million tonnes[52] mainly produced from small-scale plants. This compares to the 265 million tonnes of conventional polymers used globally in 2010[53]. This represents a barrier to the use of bioplastics in terms of volume restrictions but also in process efficiency gains, which relates to economic and in the case of cellulose, environmental barriers.

- **Unsustainable use of land**: in order to produce bioplastic feedstock additional land is required compared to conventional alternatives, this ranges from around $0.13m^2\ kg^{-1}$ for cellulose to $3m^2\ kg^{-1}$ for PHA. However, current land use is not always managed at optimal efficiency and it has been estimated that between 250-800 million ha of agricultural land could be used without encroaching on areas of high ecological or social value. Based on bioplastic production estimates up to 2020, this would only account for between 0.1-0.3% of this available land and as such land use is not a barrier to their use. However, if used unsustainably, on ecologically or socially valuable land or releases high amounts of stored carbon, this is seen as a barrier. It should also be noted that if bioplastics are sourced from land used to produce food crops there can be a perception barrier to their use.

- **GHG emissions**: cellulose films currently have higher GHG emissions than conventional PP film equivalent packaging. Whilst this may change as process efficiencies improve, this is currently a barrier to using this material as it does not currently offer the environmental advantages seen by the other bioplastics researched.

- **Mulch film removal from land**: current UK legislation requires agricultural films be removed from the land for disposal. This represents a legislative barrier to the use of starch mulch, whereby it is designed to remain on the land and is likely to be irremovable as a result of the commencement of the

[52] Derived by the authors of this report based on public announcements and personal correspondence with manufacturers

[53] Plastics Europe Market Research Group, April 2011

degradation process. Whilst these restrictions remain in place, the opportunities offered by this bioplastic cannot be realised.

- **Poor public understanding and identification**: as a result of the public not being able to identify materials as bioplastics, segregation possibilities are restricted. Additionally, a lack of understanding concerning the materials is considered to limit consumers' willingness to pay for the materials.

- **Landfill restrictions:** the Landfill Directive sets targets which restrict the total amount of biodegradable municipal waste (BMW) going to landfill in 2020 to 35% of that produced in 1995. The disposal of bioplastics to landfill should therefore be avoided which is a barrier to its use if not disposed of appropriately.

5.5 Bioplastic Opportunities

This study has identified a series of opportunities offered by the bioplastics researched. These are:

- **Reduced GHG emissions**: most of the bioplastics assessed were found to offer lower GHG emissions over their life cycle compared to their conventional alternatives[54], for example PLA offers 30% less emissions compared to PP per kg on a cradle to gate basis. This opportunity is greatest in instances where the bioplastic currently offers the same performance using less material, such as starch mulch film which is three times lighter than an LLDPE film and where enhanced functionality is offered, such as shelf-life performance, which is currently claimed for PLA and cellulose in certain applications.

- **Reduced use of non-renewable resources**: all the bioplastics assessed use renewable feedstocks for production, and as such offer a reduction in the use of non-renewable resources. For example, the conventional polymers assessed use around 70-130MJ per kg which compares to most of the bioplastics being under 10MJ per kg. As a result, bioplastics offer a potentially sustainable opportunity to reduce the reliance on non-renewable resources.

- **Composting/ anaerobic digestion**: most of the bioplastics assessed are compostable, and where UK recycling rates are poor (domestic film, non-

[54] Excluding the effects of indirect land use change, which have not been measured in most studies.

bottle rigids and multi-layered materials) or packaging is heavily contaminated, this provides an opportunity to divert waste from landfill. However, this opportunity is restricted as outlined above, by limited UK collection and processing capacity, a lack of householder knowledge and facility operator concerns.

- **Agricultural film disposal**: starch mulch has been shown to offer an environmental advantage over conventional alternatives. This is primarily evidenced by the fact that three times less film is required, but they also do not require removal from the land for disposal. However, further research into the impacts of the mulch degradation on the land is required.

- **Renewable conventional plastics disposal**: these plastics, such as the renewable PET researched, offer an opportunity as they do not need to be distinguished by consumers as being different to conventional plastics. As a result, they do not require any changes to the current waste management system.

- **Job creation**: the use of bioplastics has been found to offer a social opportunity in the anticipated global net increase in jobs. The employment sector is estimated to remain steady in the manufacturing and lower supply chain stages, with the increase stemming from those jobs created in the agricultural sector. This increase is modest, estimated by 2020 to represent around 20,000 new jobs globally, but remains an opportunity for the bioplastic market.

It is acknowledged that the bioplastic assessment made in this report and as such the conclusions drawn are based on an incomplete dataset and that of a fast-moving market. As a result the conclusions should be reviewed at regular intervals.

6 Recommendations

The recommendations provided in this Section are a possible set of tools that could be used to increase the use of bioplastics in the UK, if this is seen as desirable in the future. These tools have been categorised into the key areas of industrial co-operation, creating awareness, policy and further research. As a result of the current political landscape those based on industry-led, voluntary initiatives as highlighted in the industrial co-operation category, are considered the most likely to be taken forward.

6.1 Industrial Co-operation

- Through an industry-led initiative across the full supply chain, stakeholders should work together in future-proofing operations for an increase in bioplastics on the market. The following suggestions are examples of suitable activities that could help in this area:
  - Development and support for a standardised labelling scheme, use of a unique colour or using bioplastic-based materials for certain applications only or UV-doping. Each of these options would allow for easier identification of bioplastics by consumers and waste managers but would require the support of the full supply chain to be a success.
  - Extension of the Courtauld Commitment to include a sustainability index, rather than a focus on GHG emissions only.
  - Industry led research into the potential enhanced properties of bioplastics, such as the extension of shelf-life, with the development of an external verification system.
  - Development and support for a labelling system based on various indicators of sustainability, including GHG emissions, non-renewable resource use, water use and land use for example.
  - Dialogue between packaging specifiers and the waste management sector, including research and development stakeholders. Having this awareness in the design stage will aid the acceptance of EN 13432 materials through AD/composting facilities and allow for the identification and segregation of bioplastics at reprocessing facilities, after which they would ideally be sent to AD/composting or bioplastic

recycling technologies rather than landfill. Additionally an independent body could help the supply chain communicate through industry directories and stakeholder events.

6.2 Creating Awareness

- A programme of public and industry engagement is required to overcome and prevent any misconceptions surrounding bioplastics, for example, those relating to unsustainable land use or that of food crop land. Current views appear to consider all bioplastics as the same, when in fact they each have their own properties and opportunities.
- In terms of environmental benefits, bioplastics have been found to offer the greatest advantages when they can offer a reduced quantity of raw materials compared to conventional alternatives, or an enhanced performance in terms of shelf life, for example. Impartial advice to interested parties, such as brand owners/retailers, surrounding these opportunities should be made available and as noted above, this would require further research as the assessment made in this report only makes comparisons of each bioplastic with one conventional equivalent.

6.3 Policy Derived

- The lessons learnt from the Biofuels sector suggest that a combination of policies and approaches need to be considered to support the development of bioplastics. These policies must have an impact throughout the supply chain. They should be clear and easy to understand so as to avoid confusion. Programmes that help develop awareness with consumers and stakeholders are also important in this approach. Other key critical aspects to avoid are any uncertainties. Therefore mechanisms that can help reduce risk should be a priority.
- Further investigation is required into the preferred waste management route (with food waste or mixed plastics) for bioplastics. Guidance to local authorities should be provided on this in order to, as far as possible, facilitate consistency in collections.

- Any future public sector financial support to new designs for AD/composting facilities should only be provided if they have the necessary pre- or post-processing adaptations so they are capable of processing EN 13432 certified bioplastics effectively.

- Introducing public procurement standards that assess environmental sustainability in more depth could be beneficial. European member states have been given political support to an increase in Green Public Procurement (GPP). The improvements have to be accomplished at the level of member states. UK Government could lead on GPP in line with the experience of the United States, as outlined in Section 4.6.

- Economic and technological barriers (production capacity) facing bioplastics could be addressed through:

    - Introducing a production incentive for bioplastics. Such credits already exist in Germany and are being introduced in France, resulting in a the lack of an even playing field across EU member states. Such a mechanism for bioplastics should encourage investment, production, and adoption of bioplastics in the UK market.

    - Establishing grants and loans to small and medium sized enterprises would incentivise production plants and industrial processes for the use of bio-based feedstocks, provided that they have proven to be sustainable and that applicable EU State Aid rules are respected.

    - This funding should also be directed to R&D as further work is needed to overcome some of these technical barriers, especially performance.

6.4 Further Research

- The conclusions and recommendations made in this study are based on an incomplete dataset and a fast-moving market; as a result they should be reviewed regularly, for example biennially.

- If AD/composting facilities continue to reject bioplastics as a feedstock, other recovery solutions such as mechanical biological treatment (MBT) could be researched and potentially supported to accept these materials and avoid them being diverted to landfill.

- In order to ensure feedstock for bioplastics is sourced from sustainable agricultural practices, Government should support and research international and national efforts to improve agricultural land productivity. This may include but not be limited to land use management, yield increases, reuse of degraded land, cropping systems etc. Manufacturers should find a suitable mechanism to illustrate to customers that their feedstock is sustainable, such as the sustainability index/label mentioned above.

- Support further research into the use of non-food crops to produce bioplastic feedstock such as grassland, waste crops and other biomass (for example shellfish waste).

- Further research is required into the use of starch mulch on agricultural land in the UK and the impacts of its degradation. If this is suitable, legislation surrounding the required removal of all mulch films from farm land should be reviewed and potentially amended to allow starch-based mulch to remain on the land.

- Further research into the benefits of improved properties, such as increased shelf-life, should be conducted. These features have the potential to enhance the environmental performance of the packaging considerably but require external verification.

- The development of Product Category Rules (PCRs) for both bioplastic and conventional plastic applications should be researched and published to support LCA methodologies. These would consider such issues as the inclusion of biogenic carbon, degradation rates and carbon accounting in land use. Such guidance would produce LCA results that are fairer and more comparable than are currently available publicly.

7 Limitations

This study has used a varied range of research techniques to identify the main barriers and opportunities of using bioplastics in the UK. Whilst the data and information used to generate the study's conclusions and recommendations is believed to be the best available, it is considered to have limitations. These are:

- The assessment undertaken is based on the current level of bioplastic use, which represents around 0.7% of the global plastics market. If this market share increased, much of the data used to conduct the multi-criteria assessment would also change, for example, the GHG emissions, job creation, land-use requirements and economic assessment. As a result the opportunities and barriers would also potentially be altered.
- The multi-criteria assessment makes comparisons between each bioplastic and one conventional plastic equivalent only, it should be noted that the conclusions drawn in the report could vary if other polymers or applications were assessed.
- Some data used within the project was based on a series of assumptions and estimates, which at the time were considered to be the most reasonable and justified. Each key piece of data used was assessed for its robustness to highlight any uncertainty, as detailed in Appendix 1 of this report.
- In some cases, data was not available to be assessed within all desired categories. These gaps, once again, meant assumptions were made or these aspects could not be assessed, placing uncertainty on the results.
- Aspects of the data used have a natural variability, such as economic information and production levels. Averages were taken to reduce the impact of these variations, but nevertheless this is a further limitation to the results.
- Much of the data used within the study was only available from one source, for example, the manufacturer, of which for many bioplastics there is only one. This meant that verification of the data was not always possible and is therefore a further limitation to the results; this is reflected in the assessment of the data's robustness in Appendix 1.

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Appendix 1 - MCA Data Robustness

Material	Environmental				Economic		Technological				Legislative		Social
	GHG emissions (kg CO2e / kg)	GHG emissions (functional unit)	Non-renewable resource use (MJ / kg)	Land use (m2 / kg)	Resin Cost ($/ kg)	Sales Value ($/ kg)	Fit with landfill & EfW system	Fit with recycling system	Fit with Compost & AD system	Production capacity (global tonnes)	Incentives	Penalties	Job creation
PLA film													
Cellulose													
Starch Mulch													
Starch Bag													
PHA													
PLA laptop casing													
Renewable PET													
PP Rigid/Film													
PP Film													
LLDPE Mulch													
HDPE/PE Bag													
Polycarbonate Casing													
PET Bottle													

Key

data is robust

data is partially robust

data is not robust