Summary Report

Biodegradable Polymers and Sustainability: Insights from Life Cycle Assessment

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Executive Summary

Over the last decade, the performance and availability of biodegradable polymers (BDPs) has developed strongly, driven by increasing interest in sustainable development, desire to reduce dependence upon finite resources and changing policies and attitudes in waste management. Most of the biodegradable polymers on the market or in development are based on renewable raw material feedstocks from agriculture or forestry.

This report reviews current knowledge on the environmental impact of BDPs, primarily from Life Cycle Assessment (LCA) studies but also from a survey of opinion on BDPs among interested parties in the BDP and bio-polymer fields.

The findings are that:

- Available LCA results usually show that BDPs have advantages over petro-chemical based polymers in several environmental impact categories including typically fossil energy consumption and global warming potential.

- BDPs have favourable eco-profiles for many applications due to their relatively low energy in manufacture, CO_2 'neutral' status for their agriculture/forestry-based organic carbon content, renewability and end-of-life value from compost or energy recovery.

- Disposal at end-of-life is a significant phase in the life cycle for capturing environmental benefit from BDPs. Changes in waste management practices in UK should provide improved disposal options for BDPs .

- BDPs can offer the potential to add value and environmental benefit through the use of by-products, co-products and wastes from other UK industries.

- Further research is needed on emissions (especially of methane) from BDPs in domestic and municipal composting and on modelling of likely future UK waste management practices applicable to BDPs. Further development is needed to establish an appropriate LCA database on BDPs.

- Certified labelling and Environmental Product Declarations (EPDs) to ISO 14025 offer good ways for presenting the environmental credentials of BDPs to consumers and businesses.

Several classes of BDPs made from renewable raw materials (RRMs) have a positive role to play in advancing UK's move towards greater sustainability by reducing environmental impacts over their life cycles. This role is likely to become more significant in the future. LCAs should be used to verify and update this view for specific cases on an ongoing basis.

Advances in BDP manufacturing processes are likely to improve their environmental performance still further compared to conventional plastics, which already benefit from economies of scale.

Introduction

The aim of this report is to provide a comprehensive review of the current knowledge on the environmental profiles of biodegradable polymers (BDPs) and to stimulate a wider appreciation of the use of Life Cycle Assessment (LCA) in explaining their possible contribution to a more sustainable society.

The review is of specific relevance to the UK but also summarises generic lessons. It is intended to provide an informed, balanced and critical viewpoint on the subject material. The main focus of the review is on BDPs made from renewable feedstocks such as starch, polylactic acid (PLA), and cellulose.

The main market segments of interest today in which BDPs play a role are:

i. packaging (food containers, wraps, nets, foams)
ii. plastic bags for the collection and composting of food waste and as supermarket carrier bags
iii. catering products (cutlery, plates and cups)
iv. agriculture (mulch films and plant pots) and
v. hygiene products (nappies, overalls etc)

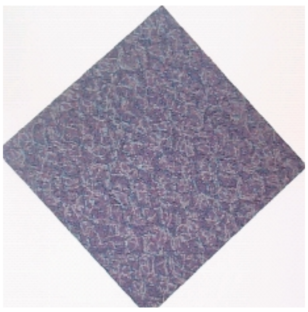
This report focuses mainly on the packaging sector of the polymers market (i and ii above), which in 2002 represented around 38% of plastics consumption in Western Europe[1] .

An increasing range of biodegradable products is now reaching the market from companies such as:

• **Cargill Dow Polymers (USA):** NatureWorks™ packaging films, bottles and textile fibres based on polylactic acid (PLA) derived through the fermentation of maize
• **GreenLight Products (UK):** GreenFill® loosefill packaging extruded from wheat starch
• **Novamont (Italy):** a range of products including films, tableware, agricultural mulch films and nappies all based on a copolymer of maize starch and polycaprolactone and marketed under the Mater-Bi® brand
• **PotatoPak (UK):** supermarket display trays and similar products based on potato starch
• **Rodenburg Polymers (NL):** packaging materials produced from waste potato starch
• **Surface Specialities UCB (UK):** cellulosic packaging films sold under the trade name NatureFlex™

NatureWorks™ PLA by Cargill Dow

Bottles



Tiles

Fibres

Textiles

1. Association of Plastics Manufacturers of Europe, 2003

Biodegradable and compostable polymers can be produced from both renewable raw materials (RRMs) and fossil materials. Currently, various BDPs are combined to improve the technical performance of the final products, to open up new applications or to reduce costs. The specific use of RRM such as maize, potato, wheat and other carbohydrate sources as feedstocks for the production of BDPs is claimed to give the final products certain advantages in terms of reduced environmental impact. These may include a reduction in the use of fossil resources, reduced CO_2 emissions and energy content and improved waste disposal options. However, the key feature of these RRM-based materials is their biodegradability and compostability, for example when used in packaging applications. This report aims to throw some light on these claims and attempt to answer the question ***'Do biodegradable polymers contribute towards sustainability?'***.

Definition of Biodegradability

A material is deemed biodegradable if it undergoes degradation by biological activity under specific environmental conditions to a defined extent and within a given time. To be designated as compostable, a material has to biodegrade and disintegrate in a composting system under standard test methods. In Europe, the criteria for biodegradability are set out in the standard BS EN 13432, 2000, which is binding when applied to compostable packaging under the EU Directive on Packaging and Packaging Waste (94/62/EC). Conformity to EN 13432 must be tested by accredited testing organisations with international experience in the specific sector.

EN 13432 requires that for a material or product to be defined biodegradable it has to fulfil the following criteria:

- **Biodegradation:** over 90% compared with standard (cellulose) in 180 days under conditions of controlled composting using respirometric methods (ISO 14855)
- **Disintegration:** over 90% in 3 months (ISO FDIS 16929)
- **Ecotoxicity:** test results for aquatic and terrestrial organisms (*Daphnia magna*, worm test, germination test) as for reference compost
- **Absence of hazardous chemicals** included in the reference list

In North America, similar criteria for defining compostability have been established by the Institute for Standards Research under ASTM D6400-99 Specification for Compostable Plastics.

Courtesy of Cleanaway

Windrow composting

Around 100 questionnaires were distributed to the networks and groups shown in Box 1. Fifteen responses were received and analysed. The returns very strongly supported LCA as being an appropriate tool to provide back-up to 'green' claims. Comments received emphasised the significance of full cradle-to-grave LCA studies and the importance of careful system boundary setting (Q4), consideration of recycling loops (especially for oil-based competitor polymer materials), and placed a high significance on the end-of-life scenarios used in the LCA models (Q5). Several of these issues are discussed in more detail later in this report. All responses considered that BDPs make a direct contribution to sustainability (Q1) and 20% of replies further suggested that cultural change in consumers would be encouraged by the wider availability of BDPs and would support improved recycling and waste management behaviour.

Box 1 Networks to whom survey questionnaires were distributed

Distribution: ERRMA Members; UK Compostable Packaging Group; Participants in UK's Competitive Industrial Materials from Non-Food Crops LINK Programme; Specific individuals

Questions

1. Do you believe that BDP can make a contribution to sustainability ?
2. Is a recognised standard for BDP products required ?
3. Is a yardstick required to back up 'green claims' ?
4. Could Life Cycle Assessment be such a tool ?
5. If LCA, what stages of the life cycle of BDPs should be covered ?
6. What are the preferred methods of disposal of BDP (Landfilling, Incineration, Domestic Composting, Municipal/Industrial composting, Anaerobic Digestion, Recycling, Other)?
7. What are the reasons to consider that BDP might lead to greater sustainability ?
8. What are the possible problems associated with BDP ?
9. What means would you suggest might encourage the wider use of BDP (Regulation, Lower prices, Lower rate of VAT, Better information, Better collection arrangements, Greater public awareness) ?

The responses showed a clear preference for certain disposal strategies (Q6) for BDPs (Figure 1). Composting, either in municipal or domestic systems, was the favourite disposal route – compostability is, of course, an inherent property of BDPs. The replies unanimously placed landfill as the worst end-of-life option for BDPs. 50% of respondents also cited reduction of landfilling as a key reason why use of BDPs might lead to greater sustainability (Q7).

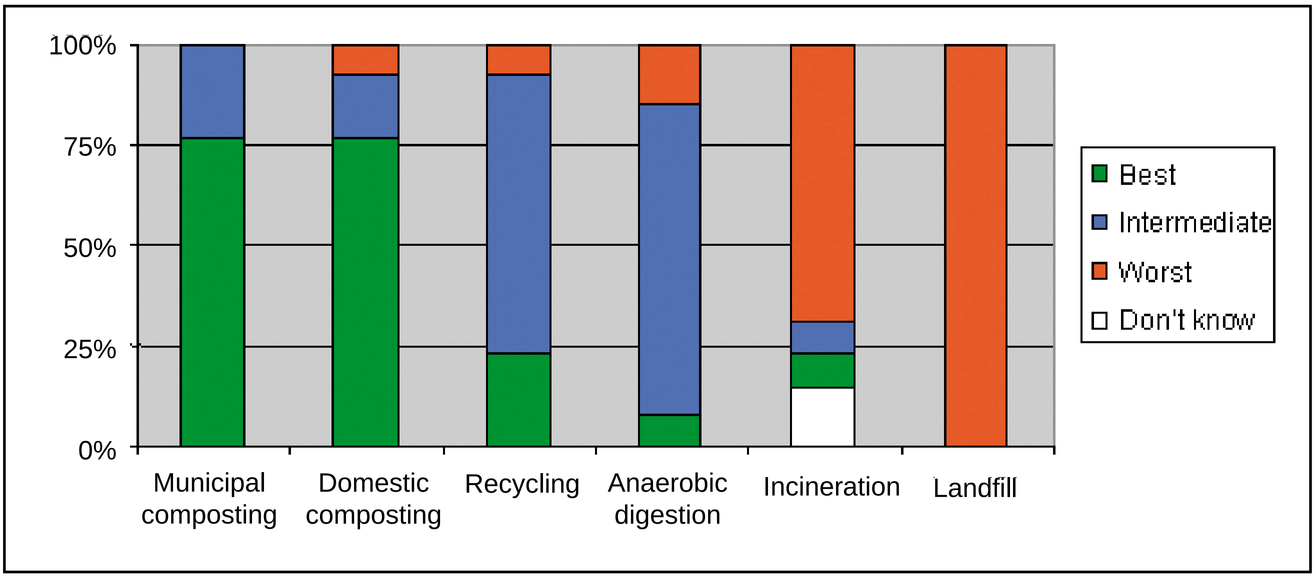


Figure 1. Survey results - Ranking of the end-of-life disposal preference for BDPs

This ranking from a relatively small but well-informed group suggests that there is a strong preference for end-of-life management for BDPs that can deliver a secondary product in the form of compost. The EU Landfill Directive recognises composting as a form of recycling. Incineration giving energy recovery is not seen to be as desirable a fate for BDP products. This is somewhat surprising as both incineration with energy recovery and composting return all or a substantial part of the organic carbon back to atmosphere at a BDP's end-of-life. Energy recovery from the BDP can be used to substitute for fossil fuel energy, and solid biomass used for generation of electricity is known to be an environmentally favourable fuel[2] . However, the survey responses may reflect concerns over the scale and investment needed for facilities for energy recovery from the combustion of waste compared with those for specifically grown biofuels (e.g. short rotation coppice), and over the potential economic and environmental values that could be gained from the environmentally sound uses of compost[3].

The survey also provided insight into some of the difficulties facing the use of BDPs (Q8). Among the main problems cited were the availability of appropriate collection infrastructure (including separation difficulties), cross-contamination of BDP and oil-based plastics recovery streams, consumer identification/acceptance of BDPs, price in comparison with conventional plastics, energy required for their production/manufacture, potential GMO sources, and functional performance. Very diverse responses were received concerning means of support for BDPs (Q9). The majority of responses indicated that lower prices for BDPs would encourage their wider use, although this was only the first choice in 25% of responses. Preferences for all other factors were were highly variable.

This survey provides a current snapshot of informed opinion on several issues surrounding the sustainability of BDPs and their future development in the UK. In summary the findings were:

- BDPs are believed to contribute towards sustainability (subject to qualifications in some responses) and LCA can be a suitable tool to assess 'green' claims.

- There is strong support for recognised standards for BDPs, especially those based primarily on renewable raw materials

- The most favoured end-of-life disposal options are domestic and municipal composting. All respondents placed landfill as the worst disposal option, the second worst option being incineration. Recycling and anaerobic digestion were intermediate.

- BDPs can be attractive 'flagship' products to help engage the public in environmental matters and promote changed behaviour.

Courtesy of Cleanaway

In-vessel composting systems

2. Reinhardt et al, 2000

3. Patel et al, Narayan and Patel,

Life Cycle Assessment

LCA is now a widely acknowledged approach to characterise the environmental impact of products and processes, and its methodology has been standardised under the ISO 14040 series. LCA enables formalised analysis of environmental impacts over the whole life cycle of a product, from acquisition of raw materials to eventual disposal. Its principal aim is to present a transparent and complete assessment of the environmental impacts of products and processes. The outcome of an LCA provides important decision support information to industry and policy-makers on technology options that minimise environmental degradation, and so is a vital environmental management tool in the move to more environmentally sound technologies[4]. The results of LCA studies are of course useful in themselves, but they also support the equally valuable concept of whole life cycle thinking when addressing environmental and sustainability matters.

Review of LCA studies

To create a detailed review of the current availability of LCA and complementary information on BDPs, approximately 100 reports, articles, standards etc were studied; the main findings are summarised briefly below.

Comparison of different LCA studies is often difficult because they commonly deal with various products, they differ in what is included or excluded from the analysis, and they may adopt differing environmental impact assessment approaches. The age of the study is a complicating factor, as technologies and data are updated and improved and environmental impact factors revised. In this review, we therefore sought generic lessons from the available studies and placed less emphasis on some of the specific comparative outcomes presented within them.

LCA studies that cover cradle-to-grave assessments based on a 'functional unit' of product and are conducted in accordance with ISO 14040 series (or equivalent best-practice guidance) are 'full' LCAs. Where studies are limited, for example by assessments being of a cradle-to-factory-gate nature or where only very limited environmental impact categories are used e.g. greenhouse gases only, then they are considered to be 'partial' LCAs. Four full ISO 14040 series LCA reports were available to this review and most of the reports/publications reviewed therefore provided partial LCA information.

The available LCA results usually show that BDPs have advantages over petro-chemical based polymers in several environmental impact categories (including typically fossil energy consumption, greenhouse gas emissions) but are less favourable or poorer in other categories (typically eutrophication, ozone layer depletion, in some cases acidification). This is a common occurrence in LCA comparisons of different materials. In addition, the different environmental impact categories are usually not regarded as being of equal weighting in terms of seriousness of effect on the environment (e.g. global warming is generally regarded as far more important than eutrophication).

On balance, BDPs are reported to have favourable eco-profiles for many applications due to their relatively low energy in manufacture, their CO_2 'neutral' status for agriculture/forestry-based organic carbon content, and their end-of-life 'value' in composting or energy recovery[5]. Data in support of these findings are presented in Table 1 and Figure 2.

Table 1. Energy and greenhouse gas (GHG) savings by selected BDPs relative to petrochemical polymers - cradle-to-gate basis (after Patel et al, 2003)

Biodegradable polymer	**Energy savings*** (MJ/kg BDP)	**GHG savings*** kgCO2 eq./kg BDP
Thermoplastic starch (TPS)	51	3.7
TPS plus 60% polycaprolactone	24	1.2
Polylactic acid (PLA)	19	1.0

* max. +/- 15% depending on whether relative to LDPE or LLDPE according to APME data by Boustead (1999/2000)

4. (UNEP, 1996; Halls, 2003; Marteel et al, 2003)
5. Patel et al, 2003 [a thorough review of some 20 studies]; Vink et al, 2003; Esterman et al, 1999; Bastioli et al, 1999

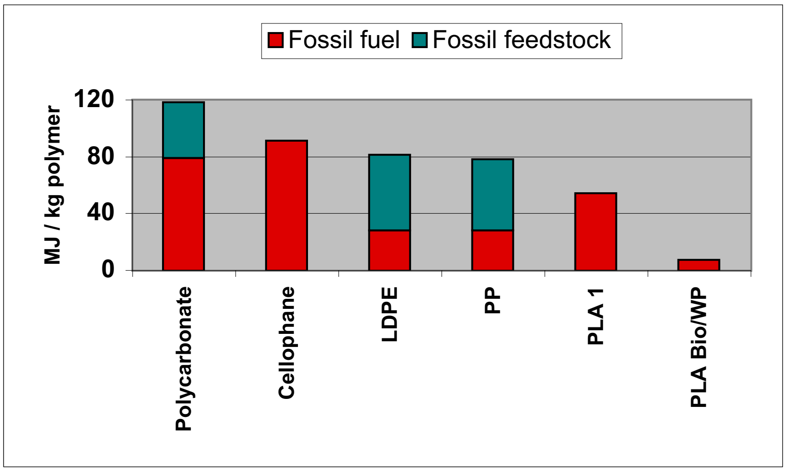


Figure 2. Fossil energy requirements for selected petroleum-based polymers and PLA (after Vink et al, 2003).
[PLA1 = polylactide first generation; PLA Bio/WP = polylactide with biomass and wind energy]

A small number of reports (6 out of about 40 LCA reports) indicated that petro-chemical plastics can have equivalent or better eco-profiles than biodegradable polymers. The main factors influencing this were energy for polymer manufacture (refuted in the public domain in the case of PLA), the effects of (an optimistic) number of recycling loops, and end-of-life disposal (especially methane generation in landfill)[6].

Most studies indicate that the end-of-life (waste management including recycling) phase of the life-cycle is significant for capturing the environmental benefits available from BDPs and bio-polymers. Changes in UK waste management practices leading to, amongst others, reduced landfilling and increased domestic and, potentially, municipal composting will help in providing for improved disposal of BDPs. BDPs can also add value and environmental benefit through the use of by-products, co-products and wastes from other UK industries (e.g. processed potato food industry and agriculture). The benefits, both of disposal through composting as opposed to landfill and in the use of by-/co-products as feedstocks for BDPs, have been demonstrated in a recent LCA for potato starch-based packaging trays[7] (Figures 3 and 4).

Photo R.J.Murphy

Figure 3. Potato starch-based packaging trays manufactured by Potato Pak Ltd, UK.

6. Gerngross and Slater, 2000; Kurdikar et al, 2001; Würdinger et al, 2001; Morken and Nyland, 2002; Bohlmann, 2003; Gartner et al, 2002
7. Murphy et al, 2004

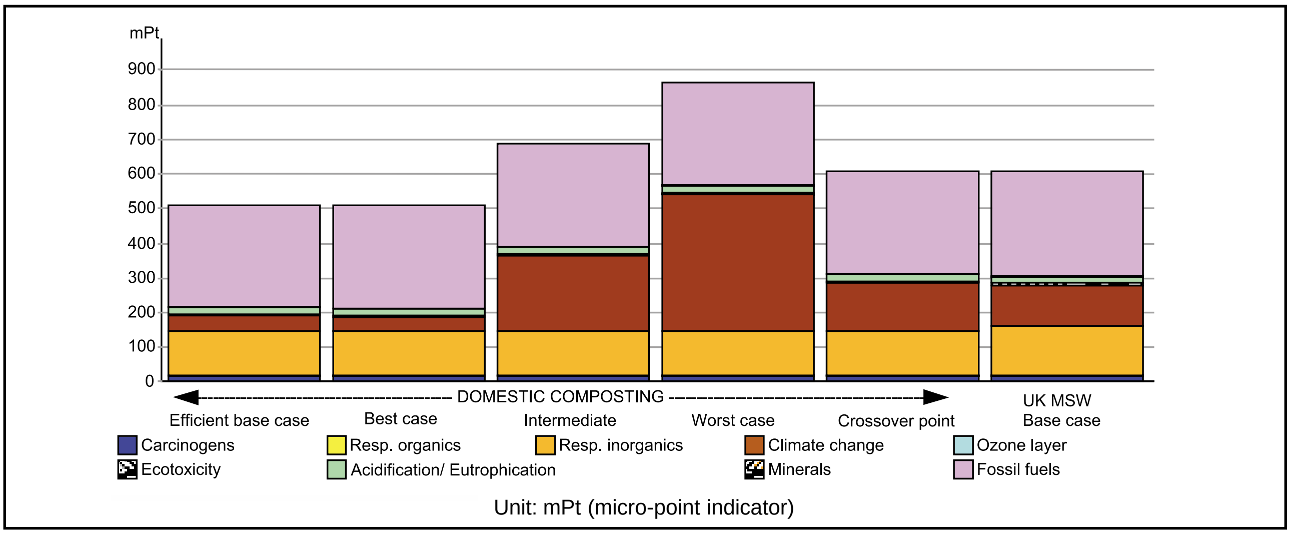


Figure 4. Comparison of the life-cycle environmental impact for UK potato starch-based packaging trays (Potato Pak Ltd) with different end-of-life disposal options - after Murphy et al, 2004.
(Eco Indicator 1999 method - higher points scores indicate greater impact on the environment)

[Efficient base case - 99% of the C-content biodegrades to CO_2, 1% to methane; Best case - 100% C-content to CO_2; Intermediate - 50% of the C-content to CO_2, 50% to methane; Worst case – 0% of C-content to CO_2, 100% to methane; Crossover point – the point at which disposal via domestic composting produces equivalent environmental impact to disposal in current MSW, this occurs when 72% of the C-content to CO_2, 28% to methane; UK MSW base case – environmental impact with disposal to current municipal solid waste 89% landfill and 11% incineration with some energy recovery].

Several of the reports touch upon the likely future needs and trends in BDP manufacture and development in the market. These can be summarised as:

- BDP manufacture is generally small-scale relative to petrochemical-based materials at present. It is likely that as scale increases technical improvements and environmental economies of scale will accrue for BDPs

- Potential exists to further develop 'durable' (essentially non- or less-biodegradable) BDPs from renewable raw materials. 'Durable' bio-polymer based materials (such as NatureWorks™ (PLA) and others) have clear potential for recycling into 'new' polymer after a first use but, due to their recent arrival in the market, this remains to be demonstrated in practice. Present BDPs and their major usage in consumer packaging offer very limited potential for recovery and recycling into 'new' polymer

- Further research and development is needed to continue to build wider ranges of technical performance of BDPs, to characterise the emissions (especially methane) from BDPs in domestic and municipal composting, to use such new data in LCA models of the environmental impact of BDPs including likely future UK waste management practice, and to organise and support an appropriate LCA database on BDPs and bio-polymers. The pro-active role taken by the Association of Plastics Manufacturers in Europe (APME) in making ecoprofiles for petrochemical-base polymers available provides a commendable example in the latter area[8].

- Certified labelling and Environmental Product Declarations (EPDs) e.g. ISO 14025 (based on full LCAs) offer good ways for communicating the environmental credentials of BDPs to consumers and businesses[9].

8. see APME web site, also Vink et al, 2003
9. Mater-Bi® PE Grade EPD, 2001

Issues of Policy and Practice

In the UK several other factors also affect the future prospects for BDPs.

Land requirement

The Government Industry Forum on Non-Food Crops (GIFNFC) estimates that in the UK the land area needed in 2005 for starch-based packaging, if made only from wheat as the source crop, would represent less than 0.01% of our current wheat area. This assessment is supported in a recent report on techno-economic feasibility of large-scale introduction of bio-based polymers in Europe[10] that indicates only modest land requirements would be needed for substantially increased quantities of bio-based polymers (assumed based solely on wheat for modelling purposes) up to 2020 (approx 0.5% to 2.5% of current total cereal land area for EU15). It is also notable that for BDPs made from RRM, the basic feedstocks can be grown locally in more or less any country and thus have the potential to support local economic and social structures.

Waste management infrastructure

Substantial changes are being implemented in the UK's waste management infrastructure. Much of this is being driven by EU policies such as the Landfill Directive, and by the realisation that the current rate of growth of household waste of 3% per year (in England) is not economically or environmentally sustainable.

Home composting

The Strategy Unit of the Cabinet Office (SU) proposes an extension of home-composting participation in England as one of five key measures to deliver a reduction in the growth rate of household waste from the current 3% figure down to 2%. BDPs contribute both directly and indirectly to this aim. The ability to compost packaging materials at home has a direct effect by diverting waste from the municipal collection system (this is actually an elimination of the waste, as it is transformed into a valuable product – compost).

Public attitudes

As indicated in the survey results of the present study, BDPs also offer likely indirect effects by being 'flagship' products that will help change behaviour, lifestyle and public attitudes to waste.

Recycling potential

The SU report also recommends increased rates of recycling which offers considerable scope for contribution to improved waste management from durable petrochemical-based polymers and some of the bio-based durable polymers like PLA[11].

Defra policy

A recent written answer by the UK Secretary of State for Environment, Food and Rural Affairs to a question in the House of Commons in February 2004 is informative:

"*Government are not taking steps to promote the use of biodegradable plastic bags. The use of degradable plastics that are made from fossil fuel, and specifically designed for disposal with no beneficial recovery potential, runs counter to the Government's aim to increase recycling. In addition, if disposed of in landfill rather than, for example, being composted, biodegradable waste breaks down to release methane, a highly potent greenhouse gas. The Government do support the development of biodegradable plastics from non-fossil sources. The Government-Industry Forum on Non-Food Uses of Crops has concluded that there is an opportunity to produce compostable packaging materials in the UK. Defra is currently drawing up a Non-Food Crops Strategy. A draft is expected to be issued for consultation later in 2004*" [12].

UK Animal By-Products Order

The composting of BDPs mixed with general food waste such as domestic kitchen waste is complicated by the UK Animal By-Products Order. The composting of material that may have come into contact with animal by-products and that is to be distributed to agricultural land or on land in close proximity to livestock is restricted to 'in-vessel' composting systems of which, at present, there are fewer than 10 in the UK. Open windrow composting (the most common municipal composting practice in UK) for such materials is not acceptable under the order. However, domestic composting of BDPs by informed householders for other uses such as gardening is perfectly practicable in the UK and is specifically encouraged in a number of schemes[13].

10. Crank et el, 2004 11. Waste Watch - Plastics in the UK Economy 12. Hansard, 2004 13. The Composting Association

UK Packaging Regulations

The UK Packaging (Essential Requirements) Regulations 2003 legislation regards the use of composting or biodegradation as a legitimate means for recovery of BDP packaging materials in the same way that other polymers in packaging are required to be recovered by material recycling or energy recovery (also suitable for BDPs).

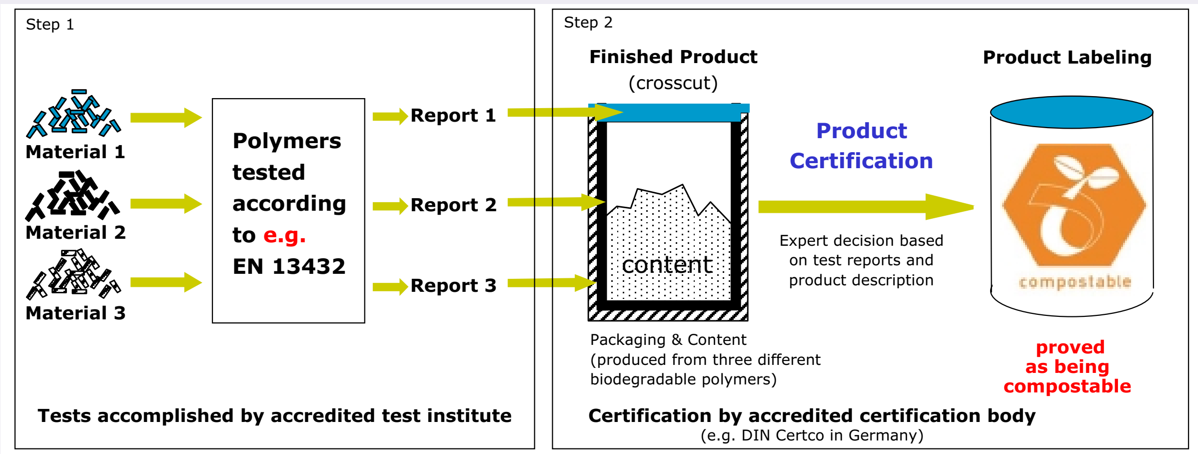
Labelling schemes

It is recognised in many reports that clear information for businesses and consumers is needed to display the attributes of BDPs correctly. LCA reports, although of high value for company internal use, for policy makers and regulators and for environment/sustainability professionals, are of limited value for day-to-day information for business or consumers. Environmental Product Declarations (based on LCA), such as for Novamont's Mater-Bi® PE Type biodegradable plastic pellet for foams, are good tools for business-to-business communication of environmental data. For communication of environmental aspects of products to the widest possible audience, and particularly to consumers, clear and credible labelling schemes in combination with supplementary additional information offer a useful route. This is currently being implemented in the UK for BDPs (see Box 2).

Box 2 Certification and Labeling of BDPs

Biodegradable and compostable plastics cannot be distinguished from conventional plastics by appearance alone. This may, therefore, lead to difficulties in sorting plastic waste for recovery. In UK, all the manufacturers of biodegradable materials now propose to use the certification scheme operated by DINCERTCO (see below). The scheme is administered by the Composting Association and the use of the registered label is restricted to products that fulfil the requirements of the certification procedure.

This scheme, promoted by the UK Compostable Packaging Group, is in line with the proposal at a European level for an Environmental Agreement (via self regulation) for biodegradable and compostable polymers based on RRM. This agreement is now at an advanced stage of consultation with DG Enterprise of the European Commission and has the support of all the major manufacturers of such materials. In North America, suppliers of approved products may use the BPI (Biodegradable Products Institute) symbol.



GM sources of RRM

Potential also exists for materials from genetically modified (GM) sources to be used in BDPs . The issue could be addressed by labelling or other attestation that the feedstocks for the BDPs are identity-preserved GM-free materials. As an example, Cargill Dow are reported to be able to offer such support through their 'Resource Offset Program' for their PLA-based products. It seems likely that other BDP manufacturers can manage their raw material sourcing or production of polymer in similar ways to accommodate concerns over GMOs.

Conclusions

Several classes of BDPs made from RRM have a positive role to play in advancing the UK's move towards greater sustainability by reducing environmental impacts over their life cycles. This role is likely to become more significant in the future.

LCAs should be used to verify and update this view for specific cases on an ongoing basis.

Acknowledgements

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References

Association of Plastics Manufacturers in Europe (2003). Plastics 2001 & 2002: An analysis of plastics consumption and recovery in Europe. Association of Plastics Manufacturers in Europe 9APME), Brussels, Belgium (http://www.apme.org/)

Bastioli, C., Facco, S., and Marini, L. (1999). Mater-Bi starch-based materials: present situation and future perspectives. Biodegradable plastics 99 Conference, Frankfurt, Germany, 19-20 April, 1999.

Bohlmann, G.M. (2003). Biodegradable packaging life cycle assessment. Annual Meeting of the American Institute of Chemical Engineers, 16-21 November 2003, San Francisco, USA

BS EN 13432 (2000). Packaging – Requirements for packaging recoverable through composting and biodegradation – Test scheme and evaluation for the final acceptance of packaging. British Standards Institution, London

Crank, M., Patel, M., Marscheider-Weidemann, F., Schleich, J., Husing, B., and Angerer, G. (2004). Tehcno-economic feasibility of large-scale production of bio-based polymers in Europe (PRO-BIP). Final Report for European Commission's Institute for Prospective Technological Studies, Sevilla, Spain.

Davis, G (2003). Characterization and characteristics of degradable polymer sacks. Materials Characterization, 51 (2-3), 147-157.

ENDS (2001). Easy Claims, difficult choices on biodegradable polymers, ENDS Report Issue 315, April 2001

ENDS (2003). Cargill Dow offers 'non-GM' maize for biopolymer feedstock. ENDS Report Issue 338, March 2003

Estermann, R., Schwarzwalder, B. and Gysin, N. (1999). Life cycle assessment of Mater-Bi and EPS loose fills. Report supervised by Composto, Bio-Consulting, Olten, Switzerland for Novamont SpA (by kind permission of NovamontSpA).

Gartner, S.O., Muller-Samann, K.M., Reinhardt, G.A. and Vetter, R. (2002). Corn to Plastics: A comprehensive environmental assessment. Proceedings of the 12th European Conference on Biomass for Energy, Industry and Climate Protection, Amsterdam, 17 - 21 June 2002, Vol. II, pp. 1324-1326, ETA-Florence 2002.

Gerngross, T.U., and Slater, S.C. (2000). How green are green plastics? Scientific American (August 2000), 37-41.

Halls, S. (2003). Facilitating uptake of environmentally sound technologies: The role of environmental decision support tools. Available at http://www.environmental-center.com/articles/article1415/article1415.htm (accessed 28 April 2004)

Hansard (2004) Commons Written Answers (23 February 2004, Column 125W), The United Kingdom Parliament. http://www.publications.parliament.uk/, accessed 28 April 2004.

Kurdikar, D., Paster, M., Gruys, K.J., Fournet, L., Gerngross, T.U., Slater, S.C. and Coulon, R. (2001). Greenhouse gas profile of a plastic material derived from a genetically modified plant. Journal of Industrial Ecology 4 (3), 107-122.

Marteel A.E., Davies J.A., Olson, W.W. and Abraham, M.A. (2003). Green chemistry and engineering: Drivers, metrics, and reduction to practice. Annual Review of Environmental Resources 28, 401-428

Morken, J and Nyland, C.A. (2002). Life cycle assessment of BioBags used for collection of household waste. Norges Landbrukshøgskole, Institutt for Tekniske Fag, ITF, Rapport 120/2002.

Murphy, R.J., Bonin, M., and Hillier W.R. (2004). Life cycle assessment of potato starch based packaging trays. Report (draft) for STI Project Sustainable GB Potato Packaging, Imperial College London, contact r.murphy@imperial.ac.uk

Narayan, R. and Patel, M. (2004). Review and analysis of bio-based product LCA's. Available at http://www.ou.edu/spp/biobased/LCAreview.pdf (accessed 28 April 2004)

Novamont SpA (2001). Environmental Product Declaration (EPD) Mater-Bi® PE type : Biodegradable plastic pellet for foams. Validate ANPA December 2001, Declaration No EPD I-ANPA-3, also see http://www.materbi.com.

Patel, M., Bastioli, C., Marini, L and Würdinger, E. (2003). Life-Cycle assessment of bio-based polymers and natural fiber composites. In Biopolymers, Volume 10, General Aspects and Special Applications Ed. Alexander Steinbüchel, John Wiley & Sons Inc.,

Reinhardt, G.A., Zemanek, G. and Junck, N. (2000). Solid biofuels or conventional fuels? A comprehensive evaluation of environmental impacts. 1st World Congress on Biomass for Energy and Industry, Sevilla, Spain, 5-9 June 2000.

The Composting Association – see http://www.compost.org.uk

UNEP (1996) Life Cycle Assessment: What it is and how to do it. United Nations Environment Programme, Industry & Environment, Cleaner Production Programme, Paris, France.

Vink, E., Rábago, K.R., Glassner, D. and Gruber, P. (2003). Application of life cycle assessment to NatureWorks™ polylactide (PLA) production. Polymer degradation and Stability 80 (2003), 403-419.

Waste Watch (undated). Plastics in the UK Economy: A guide to polymer use and opportunities for recycling. Available from http://www.plasticsintheuk.org.uk/, accessed 28 April 2004

Würdinger, E., Roth, U., Wegener, A., Peche, R., Rommel, W., Kreibe, S., Nikolakis, A., Rüdenauser, I., Pürschel, C., Ballarin, P., Knebel, Borken, J., Detzel, A., Fehrenbach, H., Giegrich, J., Möhler, S., Patyk, A., Reinhardt, G.A., Vogt, R., Mühlberger, D., and Wante, J (2002). Kunststoffe aus nachwaschsenden Rohstoffen: Vergleichende Ökobilanz fur Loose-fill-Packmittel aus Stärk bza. Polystyrol. Endbericht (DBU-Az. 04763), March 2002, available at http://www.ifeu.de/englisch/agri/seiten/a_ref3.htm

List of Abbreviations

APME	Association of Plastics Manufacturers of Europe
BDP	Biodegradable polymer
DTI	Department of Trade and Industry (UK)
EPS	Expanded polystyrene
EPD	Environmental Product Declaration
ERRMA	European Renewable Resources and Materials Association
EU	European Union
GIFNFC	Government Industry Forum on Non-Food Crops (UK)
GM/GMO	Genetically Modified (Organism)
HDPE	High density polyethylene
ISO	International Organisation for Standards
LCA	Life cycle assessment
LDPE	Low density polyethylene
MSW	Municipal Solid Waste
NNFCC	National Non-Food Crops Centre (UK)
PE	Polyethylene
PHA	Polyhydroxyalkanoates
PLA	Polylactide, poly lactic acid
PP	Polypropylene
PS	Polystyrene
RRM	Renewable Raw Material
SU	Strategy Unit of the (UK) Cabinet Office

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