Project Report

Life Cycle Assessment (LCA) of Potato Starch Based Packaging - Strategic Industry Report

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Preface

Together with the report *Sustainable GB Potato Packaging - Supply Chain Report*, this provides an assessment of the options for sustainable production of biodegradable packaging from GB-produced potato starch.

The British Potato Council became involved in and coordinated this one year Sustainable Technologies Initiative LINK project in order to bring leading researchers at PIRA International and Imperial College, London, together with representatives of the supply chain. A consortium including potato producers and processors were involved in the work, providing advice, information and guidance.

This work has demonstrated that supply of by-product potato starch recovered from potato processing operations is a viable alternative to starch produced under the EU subsidy system and imported, having advantages over this on three main counts:

- Economic – this benefits both PotatoPak, the specialist company producing the packaging who played a lead role in the consortium, and the GB industry as a whole by increasing efficiency and adding value
- Environmental – the Life Cycle Assessment has shown that potato starch based packaging has benefits over commonly used plastic-based alternatives, and GB-produced starch has benefits over imported
- Properties – over the course of the project the properties of the finished packaging material have been improved, including the moisture-resistance and production cycle-time and therefore cost

Summary

This study has aimed to identify, using Life Cycle Assessment as the principal tool, the environmental impacts of the production and use of potato starch-based packaging (PSBP) made from purpose-grown potato starch imported from the EU or a 'hypothetical' UK source of purpose-grown potato starch or from recovered by-product starch derived from UK potato food processing operations (recovered UK starch). The study was conducted in accordance with the guidelines for LCA under ISO 14040 series of international standards. The identification of environmental impacts of various waste management options for this class of materials was an additional aspect that received specific attention during the project.

As far as the three production scenarios were concerned, PSBP derived from recovered UK starch would contribute to a clearly reduced overall environmental impact compared with PSBP production from purpose-grown EU or UK starch. These reductions were mainly achieved through the use of a potato starch as a by-product as a principal raw material, thus eliminating the environmental impacts associated with the production, harvesting, storage and transportation of potato crops, including seed potatoes. A particular contribution towards environmental impacts for the purpose-grown starch scenarios was the energy requirement associated with starch processing operations.

The results of the impact assessment for the disposal scenarios revealed that efficient domestic composting contributed to a reduced overall environmental impact relative to current UK municipal solid waste (MSW) management practice. The impact reduction under efficient domestic composting stem from a reduction in methane emissions assumed from landfilling of MSW and indirectly from the elimination of requirements for transportation of solid waste and operational impacts from MSW. Modelling inefficiently managed domestic composting showed that the overall effect would be to make the life cycle impacts greater than those with current MSW practice. The most dramatic environmental impacts from inefficient domestic composting arose from the assumed anaerobic biodegradation of PSBP trays, producing emissions of gaseous methane. These emissions contribute towards the accumulation of atmospheric greenhouse gasses, impacting on global warming and climate change.

The LCA work has shown that :-

1) The use of recovered by-product UK potato starch is a preferred source of starch for minimising environmental impact over the life cycle of BSBP trays

2) Starch acquisition and processing before tray manufacture is generally the life cycle stage contributing most impact to the overall life cycle in the purpose-grown potato scenarios.

3) Well managed domestic composting was a superior disposal strategy in environmental terms than current conventional MSW for PSBP trays

Background to the Project

For many short-lived applications, long-lasting polymers have been over-engineered for stability with the result that the durability imparted to products manufactured from these materials cause them to persist long after they have served their useful function. There seems to be a touch of the absurd in wrapping a sandwich in a plastic package that will last for fifty years after its contents have been eaten, particularly when inadequate consideration has been given to the ultimate fate of that packaging material. The consequence of this has been the transformation of irreplaceable fossil resources into accumulations of persistent plastic waste. It is increasingly difficult to justify this situation at a time when concern over the preservation of resources, ecosystems and the pressing need for sustainable waste management are now areas of mainstream public interest.

Biodegradable packaging manufactured from several starch sources including potatoes, maize, wheat, tapioca and rice, exploit strong, pliant materials derived from biomass, as polymer production feedstocks. These provide an alternative to the dependence on conventional petrochemical plastics from finite oil and gas reserves, and allow products made from these materials to degrade, rejoining natural biogeochemical cycles. As well as crops grown specifically as raw materials, agro-industrial 'waste' streams offer promise as a feedstock. Not only are they cheap, but their conversion solves another environmental problem by turning by-products into useful commodities, thus reducing the environmental impact associated with their disposal. Regions without scope for crop expansion could still benefit from this approach, both economically and ecologically. Possibilities also exist for the diversification of agriculture out of food production and the generation of rural employment. This shift to renewable resources is therefore of major interest in a number of key areas including packaging.

When considering overall production costs, factors such as the depletion of natural resources or the environmental burden of waste management are seldom taken into account. These hidden environmental costs are thus externalised from the true cost of production, but nevertheless must be borne, either at the expense the environment or in prevention and remediation costs. The continued dependence of the plastics packaging sector on exhaustible fossil reserves, as well as the burgeoning waste management problems facing both industrialised and industrialising countries, brings the issue of these environmental externalities ever more sharply into focus. We are already witnessing examples of EU regulations, put into place in order to create incentives for packaging materials conforming to European waste management strategies. These measures can be viewed as methods of internalising hidden costs, which hitherto lay external to the true cost of production.

The aim of this report is to present environmental information on biodegradable potato starch based packaging (PSBP) using Life Cycle Assessment (LCA).

Polymer Biodegradation

The biodegradation of polymers involves hydrolysis and scission of susceptible polymer main chain linkages by enzymes, produced by microorganisms, which leads to a reduction in polymer chain length and molecular weight, and ultimately in the chemical or physical breakdown of the material. However, many synthetic polymers do not contain easily hydrolysed linkages and most petrochemical-based plastics are inherently water-repellent, which impedes potential enzymatic reactions. Polyethylene (PE), polystyrene (PS), and polyvinyl chloride (PVC), are but a few of the common commodity petrochemical polymers whose high molecular weights retard enzyme reaction times to such an extent that they are considered non-degradable.

This resistance to decomposition has bee an important reason why conventional plastics have displaced more traditional but degradation-susceptible materials such as paper, leather and wood. However it has now been recognised that the build up of plastic waste in landfill sites and the persistence of littered plastic items present serious environmental concerns. In addition, the dependence of petrochemical plastic upon raw materials based on non-renewable fossil reserves is another factor warranting the investigation of alternatives.

Developed since the early 1970s, the current generation of biodegradable polymers based on starch - obtained either from potatoes, maize or cereal crops - now commonly comprise proportions of starch in the region of 90%. Certain types of single trip packaging can be produced from starch with good performance properties and inherent biodegradability and this is one production application in which both commercial and environmental benefits may accrue. Production of the modified starch involves first processing and *destructuring* the starch granules, preparing the destructured starch with other ingredients, and then treating the mixture in a high pressure thermoforming process which results in the *plasticisation* of the starch. The provision of many properties such as mechanical strength is obtained through this thermal treatment..

Relevant Regulatory and Economic Measures / Recommendations

Several pieces of EU and UK legislation and measures aiming to create the economic and regulatory framework required for medium to long-term sustainable waste management, as well as providing clear signals to packaging manufacturers, local authorities and the waste management industry, are directly relevant to the production and disposal of PSBP. These are summarised in Boxes 1 – 3.

BOX 1: EU LANDFILL DIRECTIVE (99/31/EC)

The aim of the Landfill Directive is to prevent and reduce the negative effects of landfill, which include the production of methane and leachates from the anaerobic decomposition of organic sources, and to conserve landfill space. Approximately 25% of UK gaseous methane emissions are said to originate from landfill sites, while organic leachates, if not correctly managed may contaminate groundwater. Quantities of biodegradable waste entering landfill in England are currently estimated to be 15M tomes/year and rising. The requirements of the Landfill Directive are to reduce the volumes of biodegradable municipal waste sent to landfill to 75% of 1995 levels by 2010 (12M tonnes); 50% of 1995 levels by 2013 (7M tonnes), and 35% of 1995 levels by 2020 (5M tonnes). This includes a 4-year derogation offered to EU countries heavily reliant on landfilling, such as the UK. UK landfill tax increases have been proposed in order to meet these objectives.

Source: Adapted from Strategy Unit, 2002

BOX 2: ESSENTIAL REQUIREMENTS (PACKAGING WASTE) REGULATIONS (94/62)

The Essential Requirements Regulations implement two parts of the European Union Directive on Packaging and Packaging Waste and came into force throughout the UK in May 1998. The broad goal of the regulations is to reduce the volume of packaging which ends up in the waste stream. There are no weight or turnover thresholds and the regulations therefore apply to all businesses packing, filling or importing packaging. Amongst other requirements, the regulations oblige packaging to be recoverable through at least one of the following: recycling; incineration with energy recovery; and composting or biodegradation.

Source: Adapted from Envirowise, 2003

BOX 3: EU ANIMAL BY-PRODUCTS ORDER (ABPO) 1999

The Animal By-Products Order (ABPO), controls the processing and disposal of animal by-products and catering waste containing meat, with the aim of minimising the possible risk of the spread of pathogens. In May 2001, it was amended to prohibit the composting of catering waste containing or potentially coming into contact with meat, including household kitchen waste, and the spreading onto land of the resulting product. The ABPO thus effectively bans the composting of such waste. Draft EU ABPO amendments will allow composting of catering waste, but only under certain conditions. *(Note added in revision – see latest DEFRA Guidance Notes available from May 2004 , BSE Division, Branch B, Defra, London)*

Source: The Composting Association, 2003

In addition to the above regulations, the UK Government's Strategy Unit has made some further recommendations as part of its 2001 review of waste strategy in England. Those recommendations relevant to biodegradable packaging are outlined in Box 4.

BOX 4: RELEVANT UK WASTE STRATEGY RECOMMENDATIONS

- Local authorities wishing to take forward household incentive schemes designed to help reduce waste volumes should be allowed to do so.
- HM Treasury and the Department for the Environment, Food & Rural Affairs (DEFRA), should consider the case for applying incentives to encourage "environmentally-friendly" products, and should consider an increase in the landfill tax to £35/tonne for active waste* in the medium term. (*essentially referring to putrescible & biodegradable wastes)
- DEFRA should continue to encourage the development of quality standards for compost.
- The case for introduction of an incineration tax should be kept under review.

Source: Strategy Unit, 2002

In order to support the regulations laid out above, as well as helping to establish the conditions for sustainable waste management to be achieved in the short term, the Strategy Unit has also proposed several key strategic investment measures aimed at bringing about a reduction in the rate of growth of household waste, an expansion of composting, and improvement in the information and advice given to households and industry on managing and reducing waste. This has resulted in several strategic investment recommendations that could have implications for emergent PSBP industry and are summarised in Box 5.

BOX 5: RELEVANT STRATEGIC INVESTMENT RECOMMENDATIONS

- An extension of home composting through a three year programme led by the Waste & Resources Action Programme (WRAP)* to help households start composting and increase composting rates among those who already participate.
- R & D innovation funding led and managed by WRAP, based on key criteria aimed at waste minimisation including mechanisms that target products impacting municipal waste streams, particularly biodegradable waste.
- WRAP should take forward measures to increase composting through the provision of advice to local authorities on kerbside collection infrastructure and expansion of markets for compost, investment support for additional large-scale primary processing capacity, and a business development initiative for small-scale emerging composting businesses.
- DEFRA & the DTI (Dept. for Trade & Industry), should take forward a programme of advice on development of new technologies including pilots for more innovative waste management practices in partnership with industry and local authorities.

(* a non-profit organisation funded by DEFRA & the DTI)

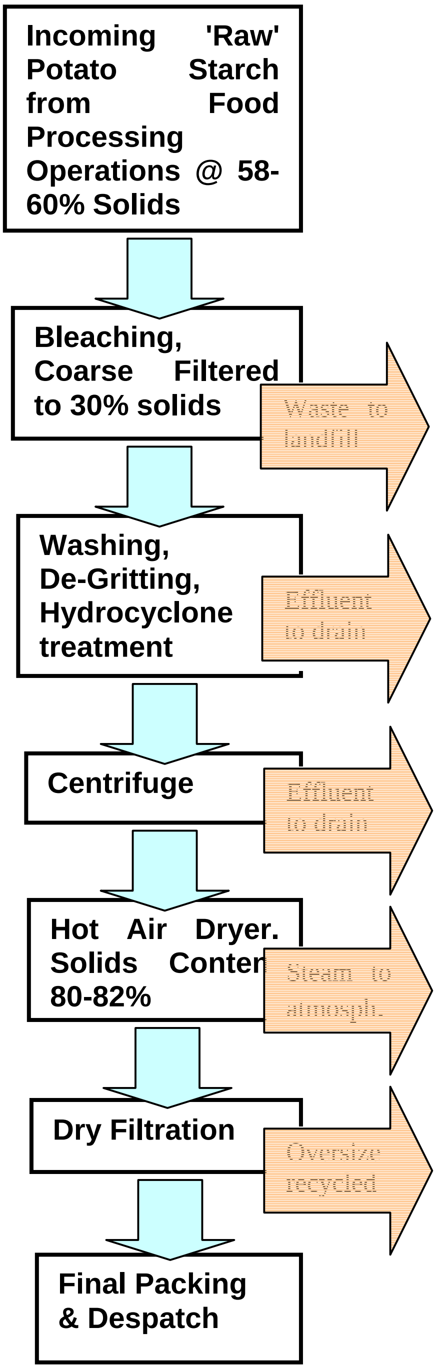
Source: Strategy Unit, 2002

The Processing of Potato Starch for Industrial Applications

Starch, the main raw material ingredient for the production of potato starch based packaging (PSBP), may be obtained from crops grown specifically for the industrial starch market or from recovered by-product starch from the potato food processing industry. In general, the availability of imported starch grown specifically for industrial uses rather than for the food processing industry, limits the price that can be charged for recovered starch.

The food processing industry uses two main methods of peeling potatoes: steam and mechanical peeling. Recovered starch derived from mechanical peeling is a useful by-product which can be reprocessed to make a higher solids material, whereas steam peeled waste water usually cannot be reprocessed as it has already been exposed to high temperatures which have 'burst' the starch granules rendering them cold water-soluble. Generally cold water insoluble/hot water soluble starches are suitable as a raw material for PSBP applications. A description of the processing of industrial starch from reclaimed by-product sources for the production of materials suitable for biodegradable PSBP applications is given below. For the purposes of this report, the processing of starch from purpose-grown industrial starch potatoes can be assumed to be a similar procedure, although the relative proportions of water and solids may vary.

FIGURE 1: STARCH PROCESSING



Prior to starch being employed in the manufacture PSBP, it must first be processed to render it amenable to production. Typical operations associated with *hot water-soluble* reclaimed Figure 1. (The process outlined is based on that used for production of *Stadex 905 starch* - Stadex Industries Ltd., Wrexham, UK.) Final hot water-soluble products, produced from 60% solids reclaimed starch are despatched after processing at ~80% solids.

The Manufacture of PSBP

Under certain conditions of temperature, pressure, shear, limited water and sufficient time, starch may be injection moulded or thermoformed to produce a material that can have mechanical properties suitable for particular structural applications.

This thermoforming process destructures the starch, rendering the material into a rigid product containing an altered molecular structure.

A typical manufacturing operation associated with manufacture of PSBP is illustrated in Figure 2. (The process outlined is based on the manufacture of 4 apple trays from '905 mix' at PotatoPak Ltd., Henstridge, Somerset, UK,).

FIGURE 2: PSBP MANUFACTURE

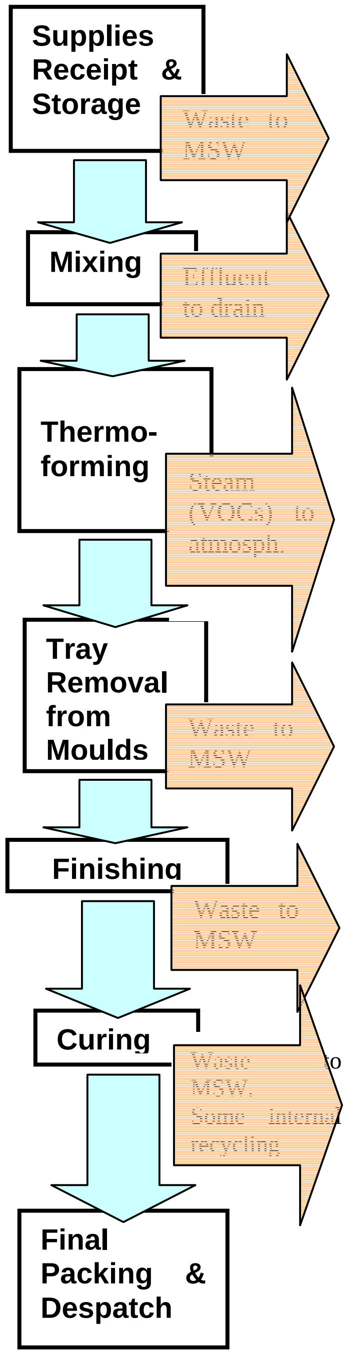


Figure 3 shows finished 4 apple trays made from potato starch manufactured by PotatoPak Ltd., Henstridge, Somerset, UK. These are currently used for the packing of organic apples.

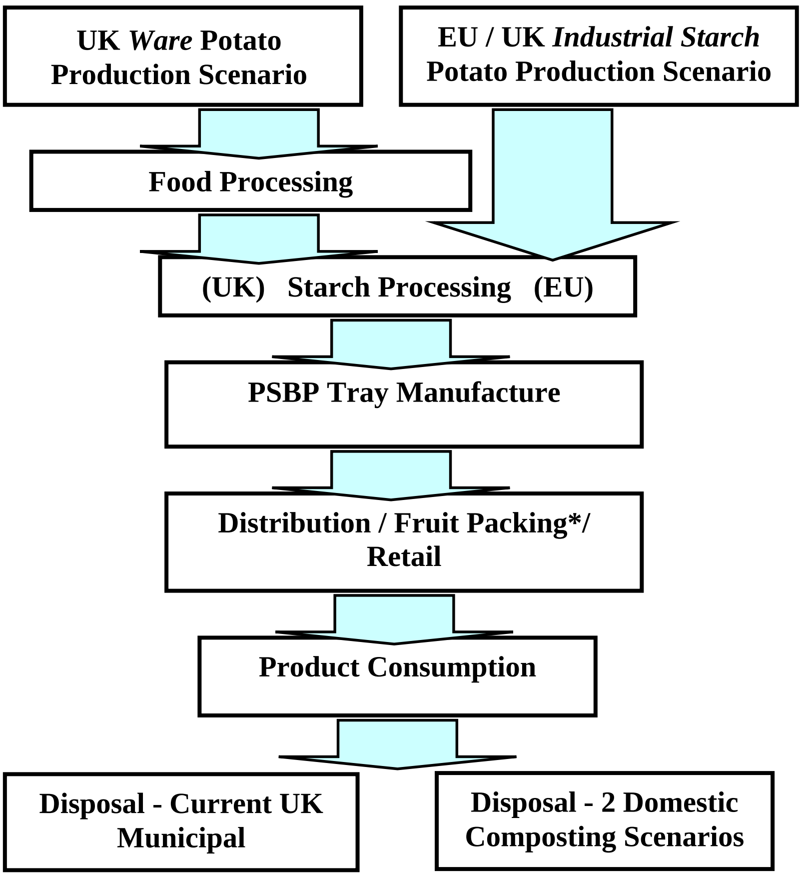
FIGURE 3: POTATOPAK LTD 4 APPLE TRAYS

Life Cycle Assessment of PSBP

The production of any consumer product carries with it inherent environmental impacts. This report seeks to quantify the significance of the environmental impacts that may originate from PSBP over the whole life cycle of the product. The LCA methodology is an environmental management tool, offering a holistic approach to assessing the environmental impacts from the acquisition of raw materials, through processing and production, supply chain, and waste management.

The overall objective of this LCA was to evaluate the environmental profile of PSBP given various realistic supply chain, production, use and disposal scenarios. The data generated for the different scenarios is compared in order to gain a broad overview of potential environmental benefits or disadvantages arising from the use of PSBP as well as providing information regarding recommended production, use and disposal options. The information and results produced in the study are intended for use primarily by those involved in the supply and manufacturing of UK potato starch based packaging in order to maximise the environmental benefits gained through any future scaling up of this technology. The LCA study was not conducted in order to make comparative assertions with other types of packaging material.

FIGURE 4: LIFE CYCLES OF PSBP



The LCA is based on an existing single-ridge tray for packing 4 apples in current commercial production by Potato Pak Ltd. Two main sources of potato starch are considered :-

1) ‘Recovered’ potato starch from food processing operations (from UK grown ‘ware’ potatoes), and
2) ‘Purpose-grown’ EU or UK industrial starch potatoes.

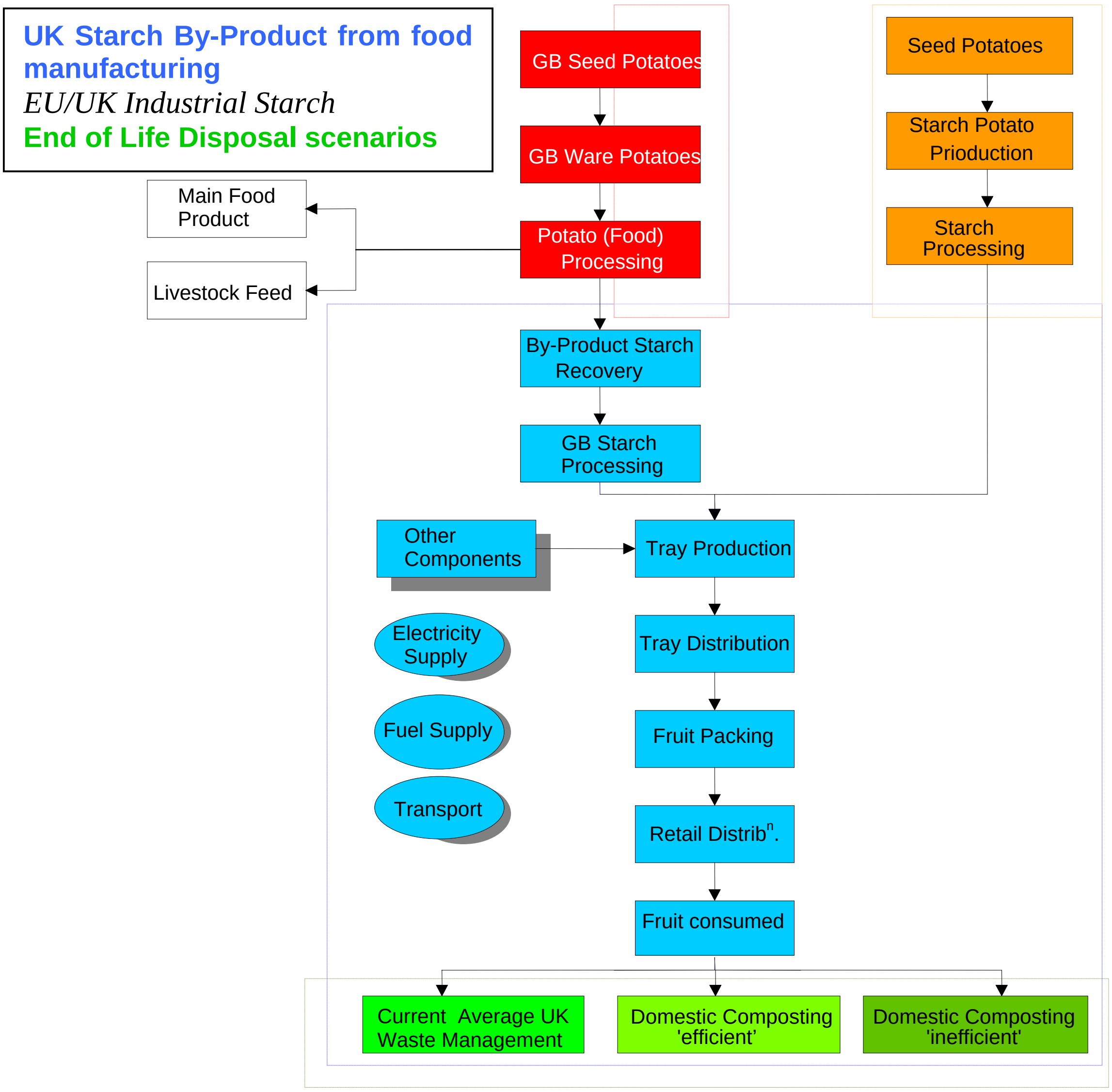
Figure 4 illustrates the life cycles of PSBP from these.

The study also investigates different end-of-life disposal scenarios

** process not included in the LCA*

The aspects of the manufacture and use of the trays (system boundaries) included in the LCA include starch acquisition and processing; manufacture of trays; distribution of trays; packing of trays with fruit; transportation of packed trays, retail of packaged goods, and disposal. Figure 5 illustrates the system boundaries of the LCA as related to the potato starch options (purpose grown production of recovered by-product) and the various disposal scenarios. The ‘Functional unit’ for the LCA study was one pallet load of apples packed in 4 apple trays (360 packed trays per pallet) – this is the quantity of trays and associated activities on which the LCA inventory is based.

FIGURE 5: SYSTEM BOUNDARIES OF THE LCA



The system boundary shows which elements (sub-processes) are included in the LCA and for which an inventory of *inputs* (e.g. raw materials, energy, transport, packaging etc) and *outputs* (e.g. emissions to air, water, land, wastes and by- or co-products)was made. In addition to potato starch, water and other ancillary materials are used to manufacture PSBP and various forms of distribution packaging are used to contain and protect the raw materials, intermediate, and finished products as they move through the supply chain. The growing and harvesting of potatoes, the processing of potato starch and the manufacture of PSBP all consume energy, fertilisers and pesticides and involve inputs into the system boundaries from the transportation of raw and intermediary materials and from product distribution. Output data is an inventory of all products, emissions and production wastes which leave the system boundaries along with any associated energy and transportation requirements.

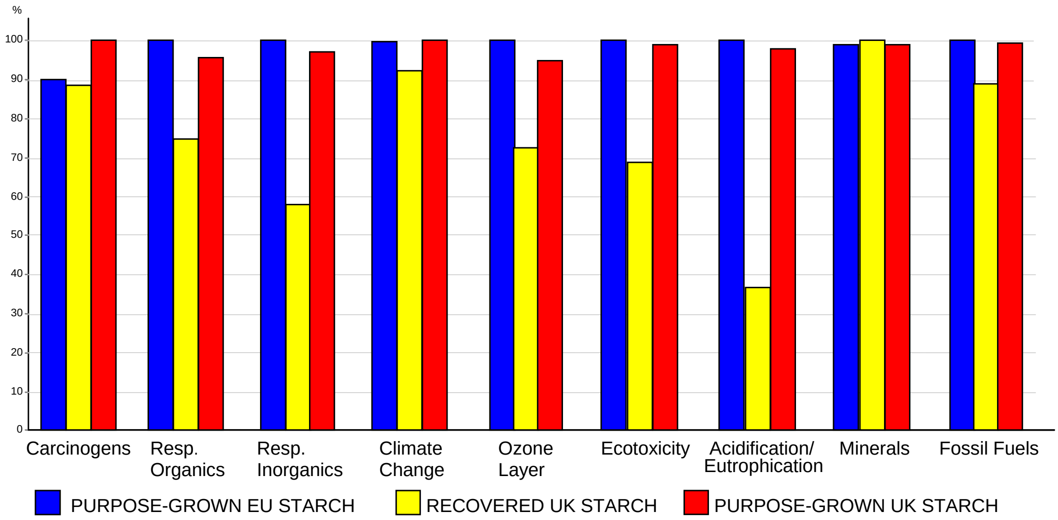
Primary data for the study were obtained directly from the industries involved, whilst secondary data were obtained from generic sources and databases. Certain constituents used in the processing of starch and PSBP production are subject to strict commercial confidentiality and while these were accounted for in the LCA, they cannot be disclosed in our data. Securing an adequate quality of data is one of the main challenges that can limit the validity of the results of LCA studies. Therefore the quality of data was carefully considered in relation to temporal, geographical, and technological coverage, as well as its precision, completeness and associated uncertainty. The inventory development required large amounts of data. Management of this data, inventory inputs and outputs and the LCA calculations was done using the SimaPro 5.0 LCA software and the Eco-Indicators 1999 Impact Assessment method (cross-checks were also done with CML 2000 method).

Environmental Impact – Sources of starch

In LCA the raw inventory results are classified into environmental impact categories. The results within each category are then characterised to produce environmental *effects scores* according to their potential effects in the environment.

A comparative assessment of the effect scores for nine separate environmental impact categories is given in Figure 6 for the production of PSBP from the 3 possible starch sources - recovered UK potato starch and purpose-grown EU and UK (industrial) potato starch. The end-of-life disposal scenario here is conventional UK MSW.

FIGURE 6: COMPARISON OF CLASSIFICATION & CHARACTERISATION LCA SCORES PSBP TRAYS MADE FROM THREE POSSIBLE STARCH SOURCES - ECO-INDICATOR 99 IMPACT ASSESSMENT METHOD



NB: Effect scores should be viewed as 'stand alone' indicators. Whilst it is possible to make comparisons within each impact category, separate impact categories bear no relationship to each other.

Clearly, production from UK recovered starch demonstrates a lower environmental impact in most categories, notably, in the two Respiratory impact categories, the Ozone Layer impact category and most significantly in the Acidification/Eutrophication impact category than the purpose-grown EU or UK starch. This greater environmental impact from EU or UK purpose-grown starch trays as compared with UK recovered starch trays arose principally because of inclusion of the agricultural activities involved in the production of potato crops for the purpose-grown EU/UK starch. In the case of the recovered UK starch, this is a very low value by-product from the manufacture of food potato products and the costs and impacts from growing the potatoes were thus fully allocated to the production of food products reflecting real world cause-and-effect (recovered starch is less than 1.5% of the food potato input (source PAS-Grantham)). All impacts for the collection and processing of the recovered UK starch into starch suitable for manufacture of Potato Pak trays are, of course, included in the analysis.

The Carcinogens impact category was the only one in which production from UK purpose-grown starch shows a greater effect score than production from purpose-grown EU starch. The lower carcinogen impact for purpose-grown EU starch originated from the higher combustion of coal for UK electricity production for the processing of starch than for the EU electricity production mix. It should be noted that the UK purpose-grown situation was equivalent or marginally better in the other environmental impact categories than the EU starch as can be expected from reduced transport distances. UK purpose-grown starch is also a hypothetical situation as there is not a current UK production of industrial potato starch due to EU quota allocations.

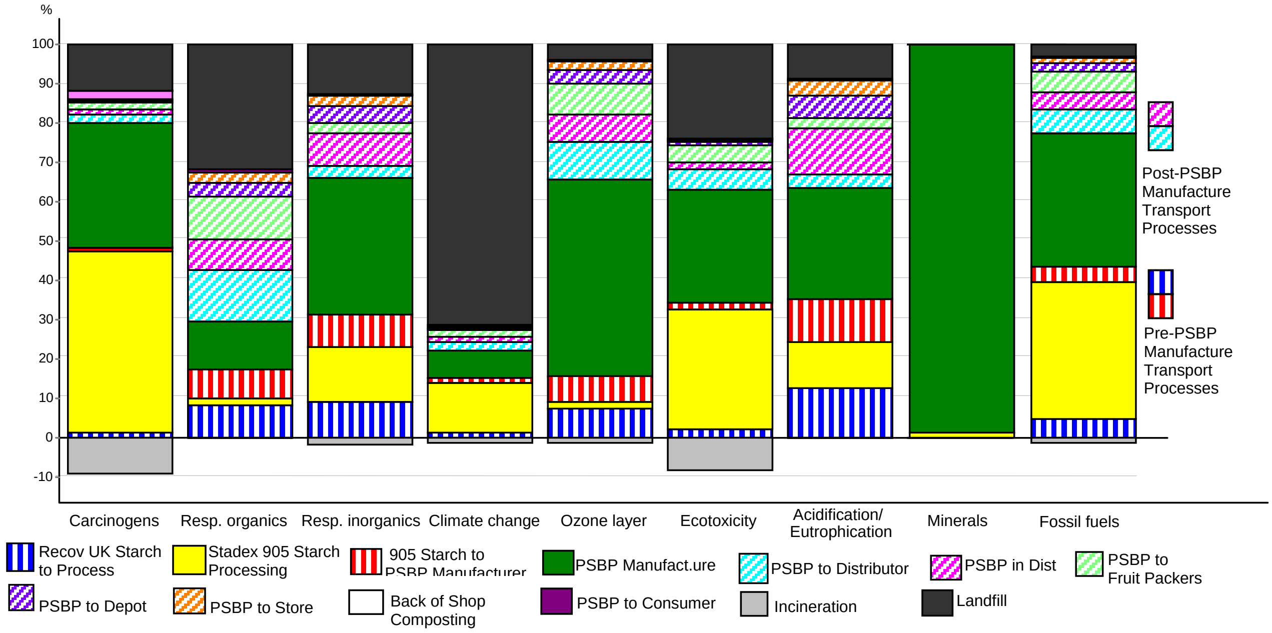
Further detailed analysis of the contribution of various stages in the life cycle to the general impact scores for UK by-product potato starch and EU purpose-grown potato starch was undertaken (see Figs. 7 & 8). It should be noted that Figs. 7 & 8 indicate the *relative proportion* of contribution of various life cycle stages to an impact category – the significance or *weighting* of these categories is considered in Figure 9 to give a general overview of the relative importance of the individual categories.

It is clear that no particular life cycle stage dominates all environmental impact categories for the trays manufactured form recovered UK starch. Overall, manufacturing at Potato Pak accounts for between 10 and 35% of most impact categories, starch processing at Stadex for about 10 to 30% of most categories and transport processes for a similar proportion. Disposal of trays to landfill has a significant impact on Climate Change through methane emission (we assumed approx. 8% of PSBP tray material generates fugitive methane from landfilling). The importance of disposal scenarios is considered in more detail later in the report.

The relative contribution of life cycle stages to each impact category for the purpose-grown EU starch differed somewhat form the recovered UK starch balance. In this case, the production and processing of the starch raw material accounted for a higher proportion of the life cycle impact contribution in most categories, generally between 30 and 70% of the impact. Other processes of importance were manufacture of trays, transport and, landfilling disposal.

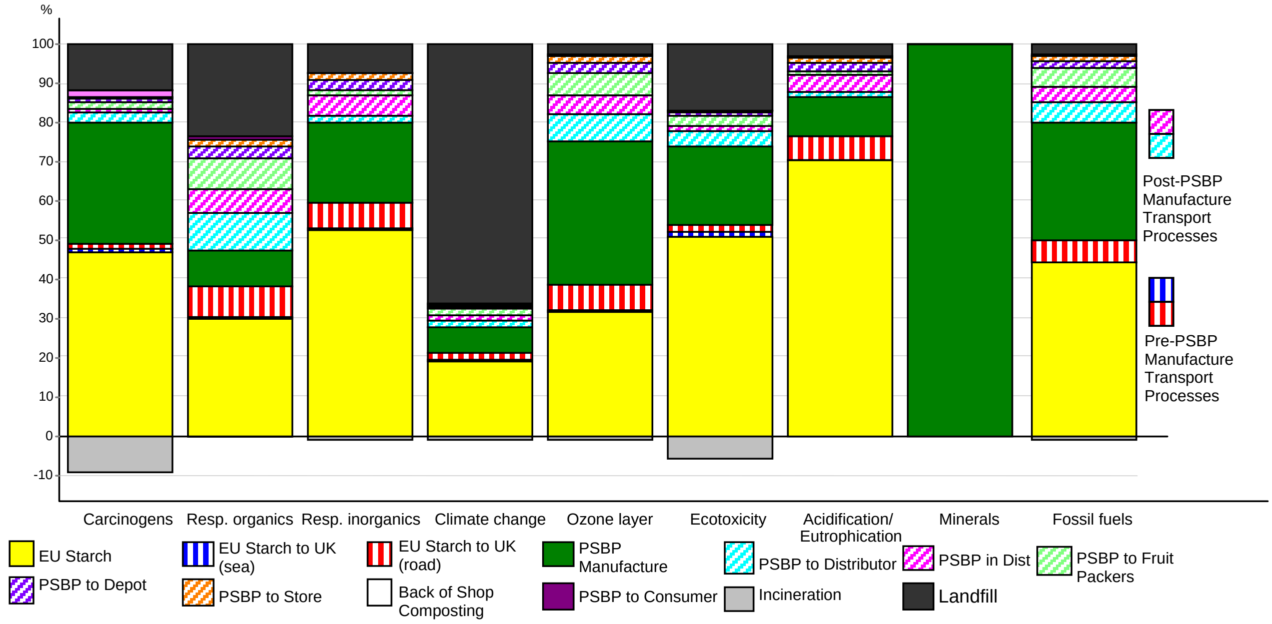
Overall, the life cycle stage analysis for each starch type shows that the acquisition of starch and its manufacturing into trays usually accounts for something between 40% and 80% of the score for most of the impact categories. The scope for improvements in order to reduce overall impact in the life cycle to these processes is related to reducing fossil energy consumption used for starch processing. The distribution chain contributed between 5 and 40% of the impact in most impact categories so there is clear scope for some reduction of overall impact in this area (although technical and economic constraints are likely to be substantial here). End-of-life disposal by landfilling was an important contributor to some categories of impact, notably Climate change. There is clear scope here for changes to MSW practice and this is supported by current and emerging policy incentives. Given the biodegradable nature of PSBP materials this element is examined in more detail in a following section.

FIGURE 7: DISAGGREGATED CLASSIFICATION AND CHARACTERISATION - RECOVERED UK STARCH



NB: All effect scores have been scaled to 100%. Those ascribed to unit process thus refer to a proportion of a total effect rather than a quantity. Colours representing particular unit processes may not correspond to those shown in other figures.

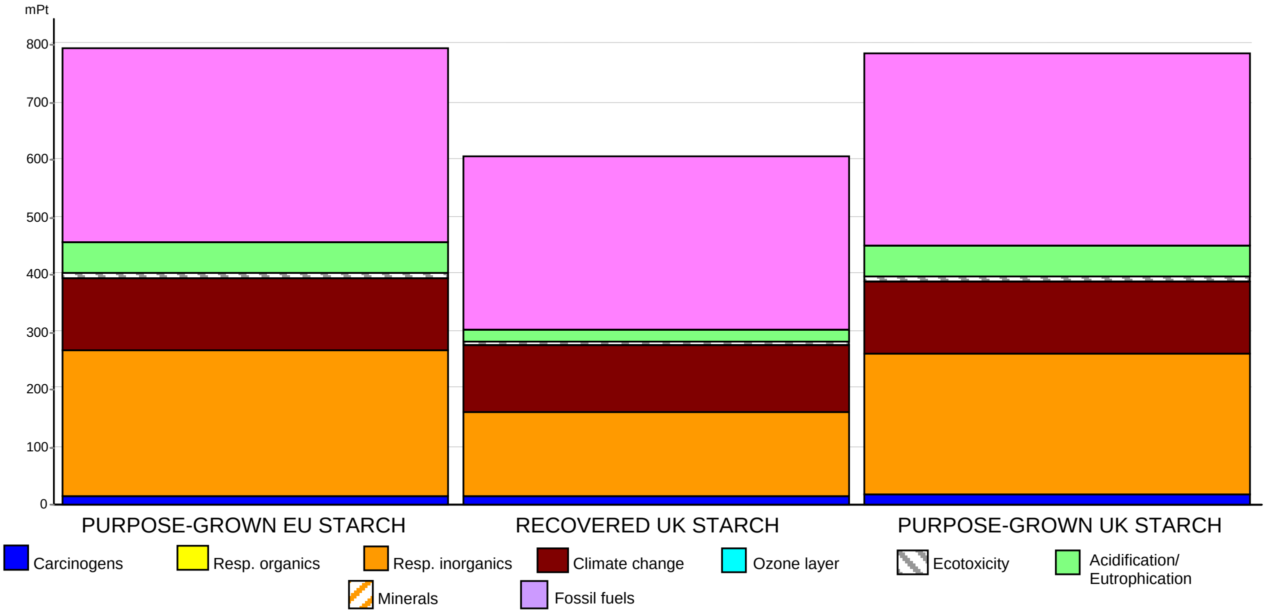
FIGURE 8: DISAGGREGATED CLASSIFICATION AND CHARACTERISATION - PURPOSE GROWN EU STARCH



NB: All effect scores have been scaled to 100%. Those ascribed to unit process thus refer to a proportion of a total effect rather than a quantity. Colours representing particular unit processes may not correspond to those shown in other figures.

Although not an obligatory part of LCA, further data analysis can be used in Eco-Indicators 1999 to develop 'normalised' (to the annual emissions of an 'average' European citizen) and 'weighted' scores (Hierarchist perspective used, see Pré e Consultants, 2003). This is shown below in Fig. 9.

FIGURE 9: COMPARISON OF UK BY-PRODUCT POTATO STARCH AND EU & UK PURPOSE-GROWN POTATO STARCH TRAY LIFECYCLES AS NORMALISED AND WEIGHTED SINGLE SCORES IN ECO INDICATORS 99.



Units: mPt (micro-point indicator)

In this summary of the LCA data the normalisation and weighting gives a perspective on the relative importance of environmental impacts. It also provides an overall 'score' in the Eco-Indicators 1999 micro-points for the whole life cycle of the PSBP trays from the different starch sources. This analysis further supports the view that there will be reduced overall environmental impact if the production of PSBP occurs from recovered UK potato starch in comparison to production from purpose-grown EU/UK starch.

PSBP Waste Management Perspectives

Before going on to analyse the scenarios for disposal of the trays at the end-of-life, it is important to consider the background to the various waste management options for their disposal. One of the potential environmental benefits of PSBP stems from its inherent biodegradability. However, in order for any benefits to be captured, appropriate strategies for dealing with PSBP waste must first be identified and modelled in the LCA. This section of the report examines these issues by setting out the likely behaviour, degradation products and potential benefits or disadvantages of PSBP under several the relevant waste management options.

Mixed Waste Consumer Disposal

Before any formal waste management option has been selected, consumer behaviour regarding the disposal of PSBP will have an influence on its environmental performance. Although in the UK, efforts are being made to increase the segregation of household waste according to material type for recycling and composting, figures show that only 13% of waste was either recycled or composted in England, the remainder being either landfilled or incinerated. Approximately 80-85% of post consumer household waste is collected unsegregated. Most local authorities collect this waste weekly and it is possible that in such an aerobic environment a proportion of PSBP product breakdown could occur within the householder's own waste bins before collection and during transportation to and from municipal collection centres and disposal facilities. Due to the large range of variables and uncertainties, mainly concerning the nature and composition of the mixed waste (the disposal environment in which the PSBP item finds itself), PSBP breakdown during this stage cannot be assumed.

Landfill

Currently in England, approximately 77% of municipal solid waste (MSW) is landfilled. Since household waste comprises 89% of MSW it therefore seems probable that a high proportion of PSBP would go down this waste management route. Landfills often comprise several successive infilled phases (and/or cells within phases), which are spread, compacted and covered daily often with soil, which is then itself compacted. Biodegradable solid waste undergoes several stages of degradation in a landfill environment. This begins with aerobic processes which then turn anaerobic as available oxygen is consumed, becoming methanogenic in the latter stages.

Waste degradation rates and the proportions of gaseous components in landfill gas are affected by the nature of the organic degradable matter present in the deposited waste. In addition, the degradation process can also be influenced by a number of other variables such as density, gas permeability, moisture contents, pH levels, temperature, and particle size. Given this range of variables and a lack of specific data, whether under initial landfill conditions an aerobic environment would be maintained for a sufficient period of time for complete aerobic biodegradation of PSBP to occur is very difficult to predict. Since it is not certain that these aerobic conditions will come about for the required period, at least a proportion of breakdown can be expected to occur during subsequent anaerobic stages of decomposition. However, as to whether the combined aerobic processes taking place during mixed waste consumer disposal (as previously described in Section 5.2.1), and the initial aerobic stage of landfill, is sufficient to bring together the conditions and time periods required for full aerobic biodegradation to take place, is obviously an area requiring further research.

Among the other environmental issues, the presence of significant methane concentrations in landfill gases originating from the anaerobic decomposition of degradable materials, has given rise to a number of serious environmental concerns. The first is an adverse impact on global warming, since methane is a greenhouse gas said to have a global warming potential (GWP_{100}) of 21 – 23 times that of carbon dioxide.

In conclusion, modern sanitary landfill design attempts to contain and stabilise materials. Thus, rather than promoting rapid decomposition, the degradation of starch trays in such an environment may actually be retarded. Landfill is in fact, more appropriate for the disposal of *inert* items such as glass and conventional petrochemical plastics, which being ‘non-degradable’, do not lead to the production of methane gasses and liquid leachates. For this reason, and to conserve diminishing landfill space, the EU has implemented a Landfill Directive aimed at reducing volumes of biodegradable waste going to landfill. It can be concluded that PSBP offers no significant environmental advantages in landfill waste management.

Thermal Treatment

Worldwide, the most developed and widely deployed form of thermal process for disposal of municipal solid waste treatment is mass burn incineration of raw waste. Incineration is the combustion of waste in a controlled way in order to destroy or transform it into less hazardous, less bulky, and more controllable constituents. Incineration may be used to dispose of a wide range of waste streams including municipal solid waste. If energy is recovered during the process it is commonly referred to as energy from waste incineration (EfW). In England, the incineration of waste accounts for approximately 11% of municipal solid waste disposal.

EfW systems utilise the calorific value of materials upon incineration to produce energy; the amount of energy derived depending on the nature of the material and particularly on its moisture content. PSBP typically have moisture contents of approximately 6-9% and approximate calorific values similar to that of wood or paper: 16.0 MJ/kg. Although this is generally sufficient to generate energy from EfW systems, PSBP materials will not produce the high heat energy of commodity petrochemical plastics commonly used in packaging applications. Furthermore, despite its apparently useful calorific value, PSBP is likely to be disposed of within mixed household waste, containing materials with far higher moisture levels and correspondingly low calorific values. Consequently, the calorific value for waste PSBP materials (~16 MJ/kg) given above is in practice, very unlikely to be achieved.

Products of the incineration of PSBP materials are expected to be ash, a proportion of which can be recycled and used in the construction industry, the remainder being landfilled. Atmospheric emissions include carbon dioxide, water, oxides of nitrogen and sulphur dioxide. Being incinerable, PSBP can be said to facilitate the maximisation of overall recycling rates through energy recovery and it thus conforms to the Packaging (Essential Requirements) Regulations 1998. However, the UK Government’s Waste Management Strategy Unit recommends keeping the introduction of a new incineration tax under review.

In terms of their overall environmental profile, PSBP can be incinerated and has reasonably high calorific values which can be recovered in EfW systems. However, this system of waste management confers few positive environmental benefits over the incineration of conventional petrochemical-based plastics which have much higher calorific values. Moreover, the biodegradable nature of PSBP becomes irrelevant as far as incineration is concerned.

Centralised Composting

Composting is the managed aerobic biological degradation of organic material in waste. Micro-organisms convert the material into carbon dioxide, water vapour and a residue known as compost, a valuable product which can be used as a soil conditioner, fertiliser, mulch and peat substitute. Two basic centralised composting systems have been developed, windrows and forced aeration, which mainly differ in the method of aeration used. The majority of centralised composting schemes use the windrows method. There has also been recently increased interest in the potential of ‘in-vessel’ systems, in which the composting environment is totally enclosed and the process is fully optimised, facilitating close control of temperature, moisture content and aeration rate.

Under ideally managed conditions the process is relatively fast, with a mature residue forming in 4-6 weeks. However, barriers exist to market development of the composting industry which include product availability, lack of proven track record, quality and consistency of finished products. Nevertheless, a vital component of meeting the current UK Government Waste Strategy targets under the EU Landfill Directive is to reduce the landfilling of biodegradable municipal waste. This involves a significant expansion in capacity for the composting of waste over the next decade to increase the proportion of the organic waste stream managed by this method. The Government has set targets to recycle or compost at least 25% of household waste by 2005, rising to at least 33% by 2015.

Composting is classified as a waste recovery operation under the 1991 EU Waste ‘Framework’ Directive. In 1999, the number of centralised composting facilities in the UK stood at 80. These centralised sites are estimated to have handled 92% of all material composted with only 7% of organic municipal wastes collected at the kerbside.

From a cursory inspection, well-managed centralised composting might seem to be the obvious choice of waste management for PSBP, given their inherent biodegradability, compostability, and their conformance to Essential Requirements (Packaging Waste) Regulations. However, the EU Animal By-Products Order (ABPO) 1999 and consequent UK Regulations, recently put in place as a measure intended to prevent the spread of pathogens into the animal and human food chain, has also had the effect of limiting this method of waste management. The ABPO defines and covers catering waste, including domestic waste, and bans the spreading on land of composted waste from these sources. The rationale behind the order reasons that being of mixed composition, these wastes potentially contain or may have come into contact with pathogen-containing animal by-products. For this reason, most commercial composting operations in the UK are generally reluctant to accept biodegradable food packaging, as this would potentially compromise the quality of their final products mainly produced from *green waste* collected from gardens and parks.

Draft EU ABPO regulations allow the spreading of composted catering waste, but only under certain conditions deemed necessary to kill any pathogens within the waste. These stipulate the composting of catering waste within enclosed reactors (or in-vessel systems) only. Thus for composting to become a realistic disposal and waste management route for PSBP, capital investment in infrastructure is required in the form of enclosed composting systems, along with significant operational expenditure in the collection of waste and the management of facilities.

Domestic Composting

Small-scale individual household composting has been practised for many years, and is traditionally part of the gardening culture of Britain. Although no national statistics exist to indicate the extent of home composting, surveys suggest that 40% of domestic rural properties and 20% of domestic urban properties compost at home. A proposed 3 year extension of home composting programmes led by the Waste & Resources Action Programme (a non- profit organisation funded by DEFRA & the DTI), aims to help households start and improve composting rates. Its specific objectives are to raise composting participation by 10% in urban and 15% in rural areas. Home composting requires the householder to keep kitchen and garden wastes separate from mixed waste, to provide a space for a compost heap or container, and to ensure that the waste material is properly aerated as it decomposes to promote aerobic decomposition

Under appropriately managed aerobic conditions, both centralised and domestic composting techniques should induce the complete decomposition of PSBP within a 7 -14 day period, the products of degradation being carbon dioxide and water. In terms of *carbon equilibrium*, these specific carbon dioxide emissions from biodegradation of the starch in composting complete a carbon ‘neutral’ cycle when the carbon sequestration into starch in the original growing green plant is taken into consideration. However, unlike centralised composting, home composting is more predisposed to problems resulting from inappropriate management. A main concern is the production of methane gas from disposed PSBP which may be allowed to biodegrade anaerobically because the potential for an adverse impact on global warming is significant, as the GWP_{100} of methane as 21 – 23 times that of carbon dioxide.

Recycling and the Implications for Plastics Recycling

The recycling of packaging materials is generally viewed as preferable to their degradability in terms of maximising the usefulness of natural resources and its overall environmental profile. However, there is little scope currently for the recycling of post-consumer PSBP. Once starch granules have been destructured during thermoforming, PSBP cannot be thermally reprocessed and are not recyclable easily back into starch processing operations.

Increased levels of use of PSBP may also have implications for petrochemical plastics recycling programmes. These fall into two main categories. Firstly, there may be a diversion of attention away from *plastics* recycling schemes with the potential hindrance of their continued development. Secondly, a more commonly expressed concern is the potential for contamination of recyclable plastics waste streams with biodegradable materials, which could decrease the end quality of the recycled plastic material or even render it unusable. These claims are disputed by representatives of biodegradable packaging interests, who point to the probability that any contamination of recycled plastics with biodegradables would be very small and easily dealt with by the addition of stabilisers to the recycled resin.

Litter Issues

The concept of the accelerated breakdown of littered packaging items was one of the original drivers behind the development of biodegradable packaging. While those materials which escape the appropriate waste disposal systems to become litter may present additional opportunities for PSBP product development, there is also a need for caution. Since the environment in which a littered PSBP item may find itself cannot be controlled, product decomposition is therefore arbitrary and under certain conditions it may take an extended period for such items to begin to decompose. An additional concern exists as to whether the promotion of packaging items as biodegradable, might lead to prospective litterers misconstruing that they can now do so with impunity - the outcome of which might be to actually increase in the amount of litter. Thus, biodegradable packaging should not be regarded as a panacea to the visible litter problem. Rendering often-discarded packaging items degradable may offer the potential to remove them both as an eyesore and as an environmental hazard. However, in order that this does not give a green light to those who might exacerbate the problem, this must go hand in hand with public education programmes.

Environmental Impacts with regard to potential disposal scenarios

The environmental impacts of the PSBP trays made from UK recovered potato starch (as this represents the least environmental impact source) according to some possible disposal scenarios were analysed. The scenarios examined were :-

Domestic composting – efficient base case

Under this scenario all PSBP is disposed of through domestic composting which is properly aerated and appropriately managed according to guidelines laid out by DEFRA. 99% of the approximate 50% carbon content of the PSBP is converted into carbon dioxide gas through aerobic biodegradation processes; the remaining 1% is converted to methane gas through anaerobic biodegradation processes.

Domestic composting - best case

Under this scenario all PSBP is disposed of through domestic composting which is properly aerated and appropriately managed according to guidelines laid out by DEFRA. 100% of the approximate 50% carbon content of the PSBP is converted into carbon dioxide gas through aerobic biodegradation processes.

Domestic composting - intermediate

Under this scenario all PSBP is disposed of through domestic composting. 50% of the approximate 50% carbon content of the PSBP is converted into carbon dioxide gas through aerobic biodegradation processes; the remaining 50% is converted to methane gas through anaerobic biodegradation processes.

Domestic composting - worst case

Under this scenario all PSBP is disposed of through domestic composting which is improperly aerated and inappropriately managed contrary to guidelines laid out by DEFRA. 100% of the approximate 50% carbon content of the PSBP is converted into methane gas through anaerobic biodegradation processes.

Domestic composting scenario – crossover point

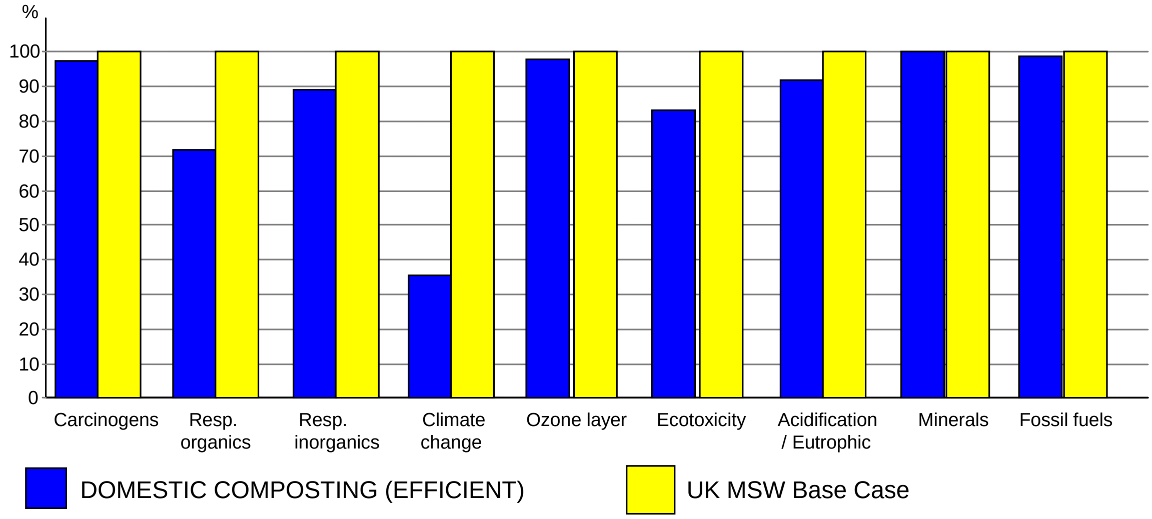
This scenario under which all PSBP is disposed of through domestic composting is used to identify the point at which the extent of inefficient management of domestic composting would confer greater damage to the environment than the UK MSW scenario. 72% of the approximate 50% carbon content of the PSBP is converted into carbon dioxide gas through aerobic biodegradation; the remaining 28% is converted to methane gas through anaerobic biodegradation.

UK MSW base case scenario

This scenario is included as a reference. Under this scenario all PSBP is disposed of to municipal solid waste by current UK waste management practice involving 89% landfill and 11% incineration with some energy recovery.

The domestic composting disposal scenarios were selected and based upon a principal design element of PSBP – their biodegradability and compostability. Further information to support the ready biodegradability of the Potato Pak PSBP tray materials was confirmed experimentally in a laboratory test at Imperial College London during the project (see Annex 1). These scenarios present an opportunity for examination of the potential for utilisation of domestic composting as method of waste management, while at the same time minimising the need for infrastructure and transportation required in the case of municipal composting. An *efficient domestic composting* scenario was contrasted and evaluated against the current UK MSW scenario. Figure 10 below, compares these two disposal scenarios.

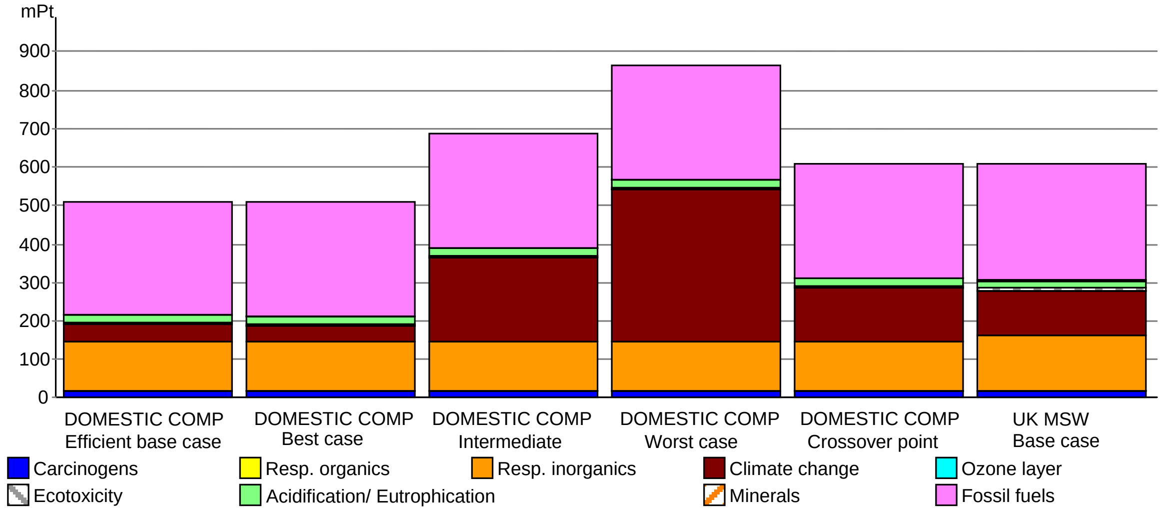
FIGURE 10: COMPARISON OF EFFECTS SCORES FOR DISPOSAL SCENARIOS (UK BY-PRODUCT POTATO STARCH TRAYS)



In the efficient domestic composting scenario, the Carcinogens; Respiratory (inorganics and organics), Ecotoxicity; Acidification/Eutrophication, all show reduced impacts compared with the current UK waste management scenario. The most pronounced reduction in impact is seen in the Climate Change category where efficient domestic composting gave a score of only 35% of that caused by current MSW. It is clear that efficiently managed domestic composting is a preferable disposal route for PSBP materials.

In order to provide an overview, the life cycle environmental impact for all disposal scenarios are shown as single scores in Eco-Indicators 1999 in Figure 11.

FIGURE 11: COMPARISON OF THE EFFECT OF THE DIFFERENT DISPOSAL SCENARIOS SHOWN AS NORMALISED AND WEIGHTED SINGLE SCORES UNDER ECO-INDICATORS 1999 FOR UK BY-PRODUCT POTATO STARCH TRAYS.



Unit: mPt (micro-point indicator)

The use of Efficiently managed (and Best case) domestic composting with UK recovered potato starch for tray manufacture represents the most favourable environmental solution for PSBP trays. Overall damage is reduced compared with the current UK waste management scenario, essentially through reductions in the Climate Change impact category. Disposal by Intermediate case managed or Worst Case managed domestic composting results in greater overall environmental impact with increases occurring in the Climate Change impact category in comparison with the current UK waste management scenario. It is clear that anaerobic degradation of PSBP is a potentially negative factor and should be avoided.

When interpreting these results from the life cycle impact assessment of the disposal scenarios, it must be borne in mind that the Intermediate and Worst case badly managed domestic composting scenarios assumes that much or all of the PSBP is composted at the homes of consumers, all of whom are incompetent in their practice of this waste disposal method. Reliable statistic do not exists regarding the number of consumers who would participate in regular domestic composting of Potato Pak packaging trays or similar materials and therefore the proportion of those who manage the technique inadequately is even more difficult to determine. However, it is believed that these scenarios are only likely to occur in practice in a very limited number of cases.

It is clear from the above that the overall environmental impact score for the life cycle of the PSBP tray is sensitive to the assumptions regarding the effectiveness of domestic composting carried out by consumers. In particular, domestic composting is seen to be the environmentally more preferable end-of-life disposal option for PSBP trays if it is assumed that fewer than 28% of consumers manage their compost in a very poor way creating substantial methane emission (with its consequent impact on the Climate Change category). Given the very high biodegradability potential of the Potato Pak tray it is a reasonable assumption that rapid aerobic decomposition/composting is the most likely outcome in domestic composting and that it is likely that very few trays would degrade in a way to release appreciable quantities of methane. Parameters close to those represented in the ‘Efficient’ Domestic Composting scenario are deemed to be the most likely to apply in practice.

Discussion of the LCA and Conclusions

As far as production of UK PSBP is concerned, the study indicates that the use of recovered UK potato starch contributes to a reduced overall environmental impact compared with production from purpose-grown starch from EU of UK sources, essentially through the use of a by-product as its principal raw material, thus eliminating the environmental impacts generated by the primary production of potato crops.

The present LCA was conducted to examine the environmental impacts arising from the life-cycle of PSBP trays. It was not formally designed as an inclusive comparative assessment against other packaging types. However, a main competitor for the type of packaging trays studies is expanded polystyrene and environmental profile data for a cradle-to-gate for this material are available from the Association of Plastics Manufacturers of Europe (APME) on a per kg of polymer basis. In order to provide for a benchmarking of PSBP with this material on this basis we have included data in Annex 2 derived from the present study for an equivalent number of packaging units.

The present study indicates that the disposal of PSBP through well managed domestic composting, rather than current UK municipal waste management practices, contributes to reduced environmental impacts overall. These general improvements were achieved through two principal means: firstly an absence of emissions (with the exception of ‘neutral’ carbon dioxide emissions), through well-managed composting, which would otherwise emanate from municipal solid waste management sites; and secondly, from an absence of any associated infrastructural and operational impacts required to process PSBP waste.

This suggests that domestic composting is the most appropriate method of waste management for PSBP. However, the modelling of badly managed domestic composting indicates an increased overall environmental impact compared to typical current UK waste management practice. This increased overall impact was identified as originating from uncontrolled emissions of methane, a greenhouse gas originating from anaerobic microbial activity occurring on the PSBP substrate.

These results raise a number of issues relevant to the entire LCA. The first of these is the availability and quality of the data used. Much of the data on the UK recovered starch, manufacturing at Potato Pak Ltd and the distribution chain was obtained from primary sources during the project and reflects current practice and development. Data for EU starch was taken from a secondary source representing mid-1990s practice. However EU industrial potato processing is a mature and well established technology and it is considered that these data are a reasonable representation of current practice and appropriate for comparison with the UK recovered starch data. The functional unit for the study was also set to be a pallet load of packed apples in order that issues of scale throughout the supply chain could be properly represented. These include consideration of wastage in tray manufacture to achieve the functional unit, ancillary packaging materials needed for distribution etc. There is considerable scope for an increased production of PSBP for fresh produce and it is considered that the results of this LCA study will be an appropriate representation for the supply of such material in the increased quantities potentially achievable over the next few years (see PIRA supply-chain report). It is likely with scale-up of production that environmental economies of scale will also accrue due to reduced wastage, improved energy efficiency in manufacture and enhanced end-of-life management. It is not anticipated that life cycle impacts for the functional unit for this study would increase with scale-up of production and use of PSBP.

Uncertainty regarding the proportion of anaerobic degradation of PSBP taking place as a result of the varying levels of competency in the practice of domestic composting was examined in some detail by means of various scenarios. We believe that the ‘worst-case’ scenario(s) are very severe given the very high biodegradability of this PSBP product, which will tend to result in quick and complete breakdown most likely before anaerobic conditions can develop in moderately managed domestic composting. However, in this area specific new research data would be of considerable value and would serve to strengthen the conclusions of the LCA.

It is nevertheless clear that effective management of the domestic composting of PSBP providing full aerobic biodegradation will minimise the overall environmental impact from such packaging and assist in meeting greenhouse gas emission targets for the UK.

Future Prospects for PSBP

Technical improvements made in the production of PSBP have provided performance capabilities approaching and in a number of cases exceeding that of the petrochemical counterparts. Biodegradable PSBP technology can at present offer a range of products that are suited to short shelf-life, single-trip packaging applications.

PSBP has a clear role to play in the future of packaging. Investment in the technological development of PSBP is likely to expand the range of processing options and properties of these materials for applications in which the advantage of biodegradability would be an important asset.

The development of large-scale production and extensive markets requires high-quality low-cost products, while the development of high-quality low-cost products requires large-scale production and extensive markets. Therefore the emerging PSBP industry is at a competitive disadvantage relative to the mature petrochemical plastics industry due to its requirement for capital investment, and this is a major economic obstacle to its successful commercialisation. Whether consumers are prepared to pay for the added functionality of a new packaging material will depend in part on the future role played by composting in municipal waste disposal. If these waste management facilities proliferate as expected in response to recent EU legislation, support will be generated for further investment in the development of PSBP, thus helping to create the economies of scale required in order to allow these products to compete economically on an equal basis with established materials.

The existence and potential environmental benefits of products derived from crop carbohydrates such as PSBP are currently poorly communicated to the general public. EU wide schemes designed to enhance public awareness, such as the *eco-labelling* of these products, could help enhance consumer demand. In a social context, degradable PSBP may call for a re-examination of lifestyles, necessitating an increased involvement of the general public and greater local authority responsibility, including a more widespread use of domestic and systems for municipal composting and public education in order to promote the appropriate application of this disposal technique. Environmental assessment using LCA have a clear role to play in creating the base knowledge for promoting such societal changes.

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ANNEX 1 Biodegradability study on PotatoPak PSBP tray material

REPORT Biodegradation of Potato Pak starch-based packaging tray material

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Introduction

'Bioplastics' are a class of materials attracting much current interest. A major perceived advantage for them is that they can be biodegraded readily in either domestic or municipal composting at their end-of-life. This can reduce overall environmental impact in the whole life cycle and, in particular, assist with waste management practice. In this experiment the extent to which specimens of Potato Pak Ltd potato starch-based packaging tray material are decomposed by common biodegradation fungi and soil and garden compost systems is examined over 9 days.

Materials and Methods

Materials Potato Pak starch-based food packing tray – approx. 2g per sample removed from fully manufactured, production trays
Supplied by Potatopak, Henstridge, Somerset

Biological challenges	*Mucor plumbeus*	*Trichoderma viride*
	Chaetomium globosum	*Coriolus versicolor*
	Soil	Garden Compost

Replication and exposure times – 3 replicate samples of pre-weighed material were placed singly on the surface of a 2% malt extract agar (MEA) medium in 9cm, vented Petri dishes. The agar had been inoculated with a spore/mycelial suspension of one of the fungal cultures immediately prior to placing of the tray material and six drops of fungal inoculum were also added directly to the material itself. The Petri dishes were then incubated at 25^{o}C for 9 days in the dark. After incubation, the specimens were removed from the cultures, surface mycelium removed by gentle scraping and weighed to determine 'wet' weight after exposure. The specimens were then oven dried at 105^{o}C for 24 hours and re-weighed to determine final oven dry weight.

Similar specimens of tray material were exposed also by burial in approx. 500 cm square bins of either a John Innes No 2 potting compost maintained at about 90% of its water holding capacity or in a well rotted compost made from green garden waste (composted outdoors over a 5 month period (Sept – Jan)) also maintained at about 90% of its water holding capacity. Soil/compost was incubated at 25^{o}C.

Check samples were used to assess the initial moisture content of the tray material before exposure to the fungi/soils. Data from these was used to calculate an initial oven dry weight of the samples for comparison with the final measured oven dry weights after exposure to the fungi/soil/compost. Control samples of sterilised tray materials exposed in sterile Petri dishes or in sterilised soil/compost for the equivalent times were used to check for hydrolysis or other non-biological (e.g. physico-chemical) degradation.

Results

The initial equilibrium moisture content of the tray material under laboratory conditions (approx. 20^{o}C, 50% RH) was 8.2% (s.d. 0.3%) on a dry weight basis.

The final moisture content (dry weight basis) of the control (sterile system) tray material and the tray material after exposure for 9 days to fungal cultures on agar in the Petri dishes or exposed in the soil or garden compost were :-

Sterile agar exposure 181 % (35%)		*M.plumbeus*	*153 % (19%)*
		T.viride	*168 % (17%)*
		C.globosum	*128 % (21%)*
		C.versicolor	*191 % (48%)*
Sterile Soil	217 % (24%)	Live Soil	477 % (78%)
Sterile Compost	209 % (23%)	Live Compost	500 % (148%)

( ) = standard deviation

Moisture content is adequate for degradation and, as expected, in heavily degraded specimens (e.g. in soil and compost exposures, see below) moisture content of the residual material has increased substantially.

The loss in dry matter of the tray specimens is given below :-

Biological exposure	Mean % loss in dry matter over 9 days*
M.plumbeus	3.6 (1.0)
T.viride	12.4 (2.0)
C.globosum	5.7 (1.6)
C.versicolor	29.9 (16.0)
Soil	71.5 (3.4)
Garden Compost	45.9 (12.8)

** corrected for loss/gain in sterile control specimens* *( ) = standard deviation of mean*

Conclusions

- Potatopak starch-based packaging tray material is *readily biodegradable*, achieving losses in dry matter the order of 45% and 70% when placed in garden compost or soil (potting compost) respectively for 9 days.
- It is expected that tray material will fully biodegrade within 2 to 4 weeks when mixed into garden compost, soil or similar material under normal (warm) conditions[1].

Some secondary observations can also be made

- Pure fungal cultures all caused some loss in dry matter although were less effective at degrading tray material than mixed inocula as represented by soil and compost

[1] Under cold climatic conditions (e.g. temps below 10^{o}C) biodegradation will take longer

ANNEX 2 Benchmarking of PSBP (4 apples tray) to APME data for expanded polystyrene sheet

Benchmarking data are presented on the *PotatoPak 4 Apple Tray* (29.20g) manufactured from potato starch, against the *Nespak 4M Tray* (5.31g) made from expanded polystyrene sheet. Both products fulfil similar functions.

The following categories are assessed: energy consumption, emissions to air, and emissions to water arising from the production of 188 packaging units in both materials.

Thermoformed EPS data used in the tables below are derived from Association of Plastics Manufacturers in Europe (APME), while PSBP data originates from the present study. Both datasets are based on 'cradle to gate' life cycle scenarios consisting of all process operations starting from raw materials production/extraction through conversion to the finished product. These include all respective upstream contributions and downstream effects within each cradle to gate scenario.

	PotatoPak PSBP	**Thermoformed EPS**
Energy Consumption (not including feedstock energy)	24.6 MJ	52.1 MJ
Emissions to Air		
Non Methane VOCs	3.6 g	9.6 g
Dust	3.3 g	3.1 g
CO	3.6 g	2.2 g
Greenhouse Gasses:		
CO_2	2,417 g	3,300 g
CH_4 (x 21 as CO_2 equiv.)	6.6 g	12 g
Total GHG (as CO_2 equiv.)	2,555 g	3,552 g
SOx	10 g	20 g
NOx	12.3 g	18 g
Emissions to Water		
BOD	1,820 mg	200 mg
$P_2 05$	7.1 mg	6 mg

