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Plastic waste: redesign and biodegradability

INTRODUCTION

Over the years, plastics have brought economic, environmental and social advantages. However, their popularity has also meant a rise in plastic waste, which brings its own economic, environmental and social issues. Of particular concern is the 'plastic soup' that exists in the world's oceans and seas, containing everything from large abandoned fishing nets to plastic bottles, to miniscule particles of plastic.

The redesign of plastic products, both at the scale of the individual polymer and in terms of the product's structure, could help alleviate some of the problems associated with plastic waste. With thoughtful development, redesign could have an impact at all levels of the hierarchy established by the European Waste Framework Directive: prevention, re-use, recycle, recovery and disposal.

This Future Brief explores current research into the redesign of plastics and developments in biodegradable plastics. It considers the implications of redesign and increased use of biodegradable plastics, as well as policy options to maximise benefits and minimise risks.

Key Facts: Plastics and plastic waste

- In 2009, around 230 million tonnes of plastic were produced; around 25 per cent of these plastics were used in the EU (Mudgal *et al.*, 2010). About 50 per cent of plastic is used for single-use disposable applications, such as packaging, agricultural films and disposable consumer items (Hopewell *et al.*, 2009).

- Plastics consume approximately 8 per cent of world oil production: 4 per cent as raw material for plastics and 3-4 per cent as energy for manufacture (Hopewell *et al.*, 2009).

- Bioplastics make up only 0.1 to 0.2 per cent of total EU plastics (Mudgal *et al.*, 2010).

- It is estimated that plastics save 600 to 1300 million tonnes of CO_2 through the replacement of less efficient materials, fuel savings in transport, contribution to insulation, prevention of food losses and use in wind power rotors and solar panels (PlasticsEurope, 2010).

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REDESIGNING PLASTIC PRODUCTS

The redesign of plastic products can occur at a chemical level and a product level. Bio-based (or bio-sourced) plastics use polymers produced from renewable sources. Since traditional plastics use petroleum, substitution by bio-based plastics can potentially reduce fossil fuel use. There are three main categories of bio-based plastics:

- Natural polymers from renewable sources, such as cellulose, starch and plant-based proteins.
- Polymers synthesised from monomers derived from renewable resources. For example, PLA (polylactic acid) is a polymer of lactic acid that is produced by the fermentation of starch, corn or sugar.
- Polymers produced by microorganisms. For example, PHA (polyhydroxyalkanoate) is produced by bacteria through fermentation of sugar or lipids.

Redesign can also occur at the level of the product. This can be with the purpose of using less plastic material or to improve a product's capacity for recycling and re-use.

DEFINING PLASTIC PRODUCTS

Biodegradable plastics decompose from the action of biological agents, usually bacteria.

Compostable plastics are biodegradable and meet certain criteria, such as rate of biodegradation and impact on the environment.

Degradable plastics include biodegradable and compostable plastics, but also plastics that degrade by chemical and physical processes, for example, with the action of sunlight.

Biodegradable plastics decompose through the action of micro-bacteria and fungi to produce a humus-like material, along with water, carbon dioxide and/or methane. Decomposition can occur aerobically (with oxygen) through composting or anaerobically (without oxygen) in landfills.

To be considered compostable, plastics have to meet certain standards. There is currently a European Norm (EN 13432) on organic recycling of packaging through composting and a twin standard (EN 14995) that applies more generally to plastics.

Purely biodegradable plastics should not be confused with 'oxy-biodegradable' plastics, which contain small amounts of metal salts to speed up degradation. It has been suggested that this process be called 'oxo-fragmentation' to avoid confusion.

Biodegradable plastics are not by definition bio-based and bio-based plastics are not always biodegradable, although some fall into both categories, such as PHA. The term 'bioplastics' is often used to refer to both bio-based and biodegradable plastics. The main applications of bioplastics are disposable plastic bags, packaging and loosefill packaging (beads and chips), dishes and cutlery, electronic casings and car components. As yet, bioplastics cannot replace all types of plastic, particularly certain types of food packaging that require gas permeability.

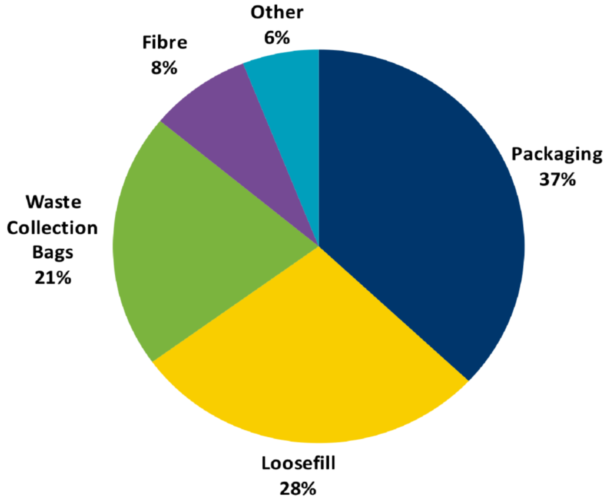

Fig 1– Bioplastics in Europe by use

POSITIVE IMPACTS ON THE WASTE HIERARCHY

Prevention – If products are designed to use less plastic, then there could be less waste. This can be done by reducing the amount of plastic, particularly in packaging, or by substituting plastic with other materials.

Re-use – Products could be designed for re-use by facilitating the dismantling of products and replacement of parts. This could involve standardising parts across manufacturers. For example, LED lamp designs could benefit from standardisation of parts (many of which are plastic) to facilitate disassembly and remanufacturing (Hendrickson *et al*., 2010).

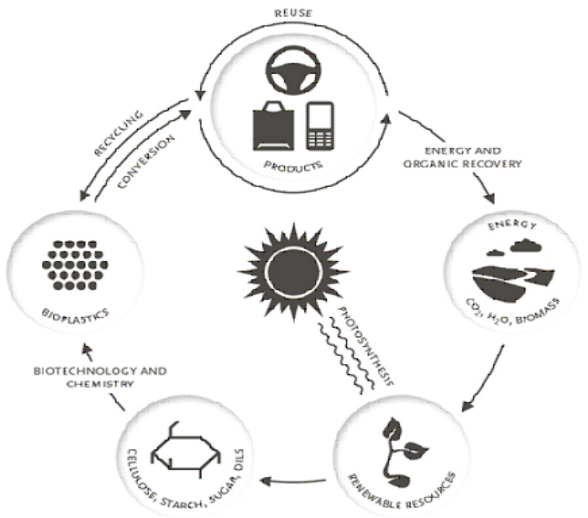

Fig 2: Idealised closed loop life cycle for bioplastics

Recycle – There are many types of plastics, some of which are easier to recycle than others, for example polyethylene terephthalate (PET). By using fewer types and colours of plastics the recycling process becomes easier. For example, some plastic water bottles are coloured which makes them difficult to recycle, whereas the process would be simpler if all bottles were clear. The use of 'intelligent' or smart polymers that undergo changes under certain conditions could also reduce disassembly time (Cerdan *et al*. 2009). For example, a polymer that changes shape when subject to magnetic or electric fields could aid the disassembly of electronic goods.

Recovery – Energy can be recovered from plastics in waste-to-energy plants. By designing products to consider the possibility of energy recovery, plastic may have a greater end-of-life use.

Disposal – Biodegradable plastics are less persistent in the environment than traditional plastics, but need specific and suitable end-of-life treatment.

Bioplastics could also help mitigate climate change by reducing our use of petroleum for the manufacture of traditional plastics. It is claimed that CO_2 emissions released at the end-of-life of bio-based plastics are offset by absorption of CO_2 during the growth of plants for their production.

ISSUES WITH REDESIGN AND BIODEGRADATION

The redesign of polymers and plastic products is already happening, and bioplastics are already on the market. However, the use of bioplastics is small (0.1 to 0.2 per cent of total EU plastics). The technology to produce them on a large scale is still in its infancy and so is the research on their impacts.

Environmental considerations:
Although significant research and product development has been done with biodegradable plastics, there is debate as to whether they actually degrade in natural habitats rather than under experimental conditions, particularly if they are present in large amounts (Song *et al*., 2009; Cho *et al*., 2011). There is also doubt as to whether they will degrade in the marine environment where heat and pressure conditions are significantly different (Thompson & O'Brine, 2010). Little is known about the effect of location, soil conditions and microorganisms on biodegradation.

Biodegradation may also influence the types and concentrations of soil microflora in disposal areas. Enrichment of soil with certain microflora which could have unanticipated risks, such as an outbreak of a new microbial disease (Sudesh. & Iwata, 2008).

Bio-based plastics require biological feedstock, which can be corn, soya, wheat or sugarcane, for example. This raises questions around sufficient farming land to cultivate the feedstock and possible conflicts with food production. If bio-based plastics were produced on a large scale, there could be competition between feedstock crops and food crops for land, possibly causing increases in food prices. In addition, feedstock crops may require an increase in the use of fertilisers and water, which would negatively affect the environment.

One solution could be the use of alternative feedstocks and industry is investigating algae for the production of bio-based plastics. The use of algae as a feedstock may have less impact because it has a high yield, can grow in a range of environments and does not compete with land-based food crops.

Although bio-based plastics are renewably sourced, this does not mean that they will reduce waste. Instead, they produce a different form of plastic waste that may require different waste management systems. Biodegradable plastics do not directly reduce plastic waste either, but make it less persistent in the environment.

The re-design of plastic products does have the potential to reduce plastic waste if it purposefully incorporates end-of-life considerations into design. However, it must be ensured that any changes in the product do not have "side-effects" further down the line during the product's use or disposal. For example, if redesign actually makes a product less durable, then it will be discarded and replaced more often, which could increase plastic waste. Similarly, it must be ensured that design for re-use or recyclability does not compromise the product's properties so as to cause unwanted environmental impacts.

Life Cycle Analysis (LCA) is used to evaluate and quantify the energy and environmental consequences associated with a product or process. Although LCA is an established method, results differ depending on systems boundaries and timing (Lazarevic *et al*., 2010).

Different LCA methods consider different environmental impacts and the effect on waste generation is not always included as a stand-alone impact. However, it may be indirectly considered through impacts such as eutrophication and toxicity.

Life Cycle Analysis of Bioplastics

There is disagreement about the life cycle impact of bioplastics and some research indicates bioplastics may have a more negative impact on the environment than conventional plastics due to their weight and production methods.

For example, a study by Tabone *et al*. (2010) using LCA methods indicated that, although some bioplastics have less impact on fossil fuel use and global warming potential than traditional plastics, they could have greater environmental impacts in terms of eutrophication and eco-toxicity. These would be caused by fertiliser use, pesticide use and land use change required for agriculture production as well as from the fermentation and other chemical processing steps.

However, European Bioplastics (the trade association for manufacturers of bioplastics in Europe) suggests that it may not be appropriate to directly compare bioplastics (which are at a very early development stage) to older materials as the latter have optimised their life cycle over time.

In their LCA review of the environmental impact of plastics, Plastics Europe (the trade association of European plastic manufacturers) considered research on two bioplastics: a PLA bottle and LDPE (Low Density PolyEthene) film based on ethylene derived from renewable resources. The benefits derived from these depended on the choice of feedstock and waste management strategies. The environmental impact of PLA bottles was more variable than PET bottles and, in some cases, production methods contributed to a more negative impact on the environment overall. On average, the PE film based on renewable resources produced 2 to 3 kg less CO_2 per kg compared to PE derived from fossil resources, but this depended on the choice of feedstock and how the waste was managed.

Economic considerations:
Over the years, plastics have saved both money and greenhouse gas (GHG) emissions because they make products cheaper, lighter to transport and, in some cases, more durable. However, redesign and introduction of new plastics will require investment.

Changes in chemical and manufacturing processes will place demands on labour and equipment. New skills and technology will be required. These could be retrofitted onto existing factories and process lines, for example, high volume monomers, such as ethylene, that are made from ethanol derived from renewable sources can be synthesised in existing polymerisation plants. However, for new polymers, such as PLA, equipment will have to be adapted and there could be an increase in the non-renewable energy required in the manufacturing chain.

It is possible that costs could be brought down by optimising polymerisation and extraction of bioplastics through the genetic modification of plants. However, methods for processing and extraction need further research and there may be stigma around genetically modified organisms (GMOs) (Mooney, 2009). Another possibility is to use organic waste materials and PET rather than biomass feedstock (Yu *et al*., 1999).

Due to development costs, bioplastics will initially be more expensive and it will take time for them to reach a critical mass before they are affordable. Depending on the strategy, the redesign of products for less plastic use and for better recyclability could potentially cut manufacturer costs by reducing the amount of virgin plastic required. However, redesign for re-use is more complex as manufacturers are generally motivated to sell more products and improved re-use could reduce the sales of new products.

Social considerations:
Plastics have undoubtedly brought social benefits over the years and will continue to do so with the development of new plastics for use in health, communications and renewable energy. The industry also provides employment opportunities.

Bioplastics and redesign can contribute to the management of plastic waste but will need better public understanding and a review of systems to produce the desired impact. Some bioplastics will require renewable feedstock and this may conflict with food security. If GM crops are used, the stigma surrounding GMOs may need to be addressed.

Social messages around biodegradable plastics are not straightforward. For example, consumers could be more relaxed about discarding bioplastic products, causing a reduction in re-use or recycling. It is currently unclear what is meant by *biodegradable* and better public information is needed. However, demand as well as supply should be considered.

Manufacturers may need to be encouraged to reconsider the current innovation cycle, which is based on selling new upgrades and models rather than longevity in design. This is especially true for electrical goods. This does not mean curbing market driven innovation, but finding ways to replace an upgraded piece of technology rather than throw the whole product away.

Case Study— Mater-Bi by Novamount

Mater-Bi is a family of bioplastics produced from plants, such as corn, and biodegradable plastics obtained from both renewable raw materials and fossil raw materials. It comes in a granular form that can be processed to create products with characteristics similar or better than traditional plastics. Its applications include catering (plates, cutlery), packaging, accessories, toys, composting bags and biofiller for the automotive sector.

Mater-Bi is biodegradable in accordance with EN 13432 and other international certification bodies. It also has a large number of end-of-life scenarios such as energy recovery and recycling as well as organic recovery through composting. In all of these it satisfies the European standards: EN 13430 (recycling), EN 13431 (energy recovery) and EN13432 (organic recovery).

CURRENT KNOWLEDGE

More accurate and regionally detailed forecasts are needed for plastic waste, waste management and environmental impacts of plastic waste. This will give a better idea of the extent of the problem and help identify where the introduction of bioplastics could have the greatest effect. Better LCAs are needed that include the impacts directly related to waste and the impacts caused by the production of feedstock, such as water use, fertiliser use and land use change. There also needs to be more agreement on methods so different types of plastics and products can be compared.

The feasibility of redesign and biodegradable plastics on a large scale requires research and evaluation, not only to study the technology and cost, but also to identify those products and polymers providing the most benefits. Currently, eco-design research lacks evidence on design for re-use and recycling. Research is needed to investigate whether current waste management infrastructure can deal with the new breed of plastics. For example, bioplastics can lower the quality of recycled materials, such as PET bottles if they are not removed during the separation stage.

The European Plastics Recyclers Association (EuPR) has suggested that, unless there are separate collection and recycling systems, both bioplastics and oxo-degradable plastics could compromise the progress that plastic recycling has made over recent years. In terms of energy recovery via incineration, there is a lack of data on the gross calorific values (GCV) of bioplastics.

Further research is also needed on the extent of production of CO_2 and methane (both greenhouse gases) when biodegradable plastics decompose.

POLICY IMPLICATIONS

The management of plastic waste involves many stakeholders and requires a range of policies (Shaxton, 2009).

For plastic redesign and biodegradable plastics to make a meaningful contribution to the problem of plastic waste, there needs to be a clearer understanding of what is meant by these terms. Standards on biodegradability, compostability and recyclability do exist and labels have been created, for example, the EN13432 compliant compostability label (see Fig. 3). However, the implementation of standards may need revisiting and currently, EN 13432 is only used in Germany, Switzerland, the Netherlands, Poland and the UK (European Bioplastics, 2011). The European Committee for Standardisation (CEN) is developing a technical specification for bio-based plastics looking at their carbon content, which should be available in 2012.

Clearer certification and labelling schemes are needed to ensure the public understand what is meant by *biodegradable*, *compostable* or *eco-friendly*. DG Environment's report on Plastic Waste in the Environment (2010) proposed that any targets on bioplastics should be combined with a labelling system and initiatives to increase public awareness and education. Labelling of plastic parts with the type of polymer they contain could also help in sorting for recycling and re-use.

Lead Markets Initiative on Bio-based Products

The European Commission has developed a set of policy recommendations together with industry stakeholders as part of the Lead Markets Initiative:

- The bio-based carbon in products shall be deducted from their total carbon footprint;
- Consider indicative or binding targets for certain bio-based products – as for biofuels;
- Allow Member States to reduce taxes for sustainable bio-based products;
- Allow bio-based plastic to enter all waste collection and recovery systems;
- Encourage public authorities to give preference to bio-based products in procurement;
- Begin a reflection process with stakeholders on product labels and information for consumers.

The Ecolabel is currently awarded to products designed for greater durability and recyclability (for example, televisions) or whose durability is increased through upgrades (for example, computers). However, it may be possible to make the Ecolabel more specific to plastic or create a plastic Ecolabel or plastic footprint, especially for packaging. There are plans to create larger-scale Ecolabels, such as for potential buildings, which could have potential to reward eco-design principles that focus on the use of plastic. The individual labelling of plastic products or plastic parts with the polymers they contain could be instrumental in facilitating re-use, replacement and recycling.

Fig. 3 EN13432 compliant compostability label

Currently R&D in the plastics industry is focused on the 'use' stage of the product. Greater consideration of end-of-life should be encouraged in both the development of new bioplastics and the design of plastic products. Initiatives such as ETAP and LIFE could help incentivise this and share best practices. Support may also be needed to expand skills and training.

Considering the variation in waste management infrastructure, impact assessments of bioplastics on infrastructure should be at a national and maybe regional level to ensure the advantages of these new plastics are not outweighed by their disadvantages. In many countries, there will be a need for more efficient sorting at source and collection systems to ensure bioplastics do not cause more problems than they address. The consultation with industry and public to ascertain practical ways to encourage redesign, re-use and repair of products will need to pay special attention to the complex nature of plastics.

OVERVIEW

- The redesign of plastics and bioplastics has the potential to reduce the use of fossil fuels, decrease CO_2 emissions and decrease plastic waste.
- More agreement is needed on the use of Life Cycle Analysis (LCA) to assess the environmental impact of bioplastics and redesigned plastics and LCAs need to focus more on end-of-life analysis.
- Clearer definitions and better labelling on the new breeds of plastics are required as well as improved public communication.
- Assessments of the impacts on waste management infrastructure should be performed at a local and national level.
- Research is needed to assess the critical mass needed to make bioplastics affordable and to identify the most appropriate plastics to substitute.

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