Case study: Bioplastic or Polyprop?[1]

A starch-based (left) and a polypropylene (right) strainer

Contents

Many proposals of sustainable development involve replacing oil and gas-derived products and services with less carbon-intensive alternatives. This case study illustrates some of the difficulties.

[1] A set of PowerPoint frames illustrating this case study can be downloaded from www.grantadesign.com/education

Bioplastic or Polyprop? - Handout

The proposal

Commodity plastics are made from fossil hydrocarbons, particularly oil. This is concern for four reasons:

- oil is a non-renewable resource and a precious one;
- using fossil hydrocarbons ultimately releases the carbon they contain to the atmosphere;
- dependence on oil exposes the industry to risk of cost volatility and supply constraints, and
- most oil-based polymers degrade only very slowly creating a long-term problem of "polymer pollution".

Bio-polymers, by contrast, are plastics made from biomass. Hydrocarbons derived from renewable sources such as corn, soya, cellulose and polysaccharides such as sugarcane can be polymerized to make bio-PE, bio-PET and other less familiar plastics such as PLA and PHA. Today they are used for packaging (NatureWorks PLA), disposable cutlery and containers (Cereplast's PLA blend, Novamont's Mater-Bi starch resin), dental care items and medical items (Cereplast) and agricultural turf stakes (Telles PHA).

Bio-polymers are promoted as sustainable substitutes for plastics derived from oil. If they are to do this they must *really* be more sustainable than oil, must perform as well as the materials they displace, be affordable and be producible on a scale that compares with that of commodity plastics.

The Bio-based Society[2] makes the following claim: *"Biobased polymers will increase in capacity to 12 million tons/year by 2020. That will equal 3% of total polymer production."* That is a statement of an anticipated sustainable development. What is the background? Who are the interested parties? How do the carbon footprint and price of bio-polymers compare with those made from oil? Can we form a balanced opinion about the claim?

Initial facts

The table lists commodity oil and bio-based polymer. Those marked with a star (*) are biodegradable

Oil-based polymers	Bio-polymers
PP	**Bio-PP**
PE	**Bio-PE**
PVC	**PLA***
PU	**PHA***
PET	**PTT**

To bring the project to life we have examples of near-equivalent bioplastic and oil-base plastic products, shown on the cover page. Here is what the maker of the bioplastic strainer says about it.

"(The company) values the well-being of you and Mother Earth, designing stylish kitchenware out of bioplastics made from a seventy percent natural corn starch blend. (The company's) entire production process uses much less fossil fuel than conventional plastic so oil consumption is less and the environmental impact to our natural resources is reduced."

[2] http://www.biobased-society.eu/2013/03/biobased-polymers-will-make-a-breakthrough-within-ten-years/

The steps

- What is the prime objective? What is its scale and timing? What is the functional unit?
- Who are the stakeholders and what are their concerns?
- What facts will be needed to enable a rational discussion of the relative merits of bioplastic and oil-based plastic products?
- What, in your judgment, is the impact of these facts on the three capitals?
- Is the proposal a sustainable development? Could be objective be met in other ways?

Where can CES EduPack Sustainable Development Edition help with Fact-finding?

The **Materials Level 3 data-table** contains property data for bioplastics and oil-based polymers. This includes price, embodied energy, carbon footprint and recycle fraction in current supply. The “Science notes” give background about recycling of plastics.

The **Eco-audit tool** allows a fast comparison of the embodied energy and carbon footprint of bio and oil-based plastics.

The **Regulations data-table** identifies government incentives and restrictions that relate packaging, waste, and the use of chemicals.

The **Nations data-table** provides background on the prosperity, environmental performance, and governance of countries from which feedstock for biopolymers might be sourced or biopolymer production located.

The **Graph facility** of the CES EduPack software allows data to be plotted as property charts, annotated and saved to WORD documents.

Bioplastic or Polyprop? – example of assessment

The numbering of the sections corresponds to that of the 5 steps of the analysis. The CES EduPack Sustainability database helps with fact-finding in ways described in the Handout for this Case Study.

Step 1: The objective, size and time scale and functional unit

- ***Objective:*** to increase global production of biopolymers to 12 million tonnes per year (3% of all plastic production), making polymer use more sustainable.
- ***Size scale:*** 12 million tonnes per year.
- ***Time scale:*** by 2020.
- ***Functional unit:*** 1 kg of plastic.

Step 2. Stakeholders and their concerns.

Here are five quotes from people and organizations that have an interest in bio-polymers.

- *"Bio-plastics make good business sense. Independent market research has shown a majority of customers would patronize a business that is "green" over one that isn't*[3]*."* (Biomass Packaging, 2013)
- *"'Sustainable' bio-plastic can damage the environment. Corn-based material emits climate change gas in landfill and adds to food crisis*[4]*"* (The Guardian, 26 April, 2008)
- *"Finding alternative sources for materials is becoming imperative as petroleum prices continue to rise*[5]*"* (John Viera, Ford's global director of sustainability and vehicle environmental matters, May, 2012)
- *"Worldwide demand for bio-plastics will grow fast over the next decade ….(driven by)… government regulation and legislation to promote sustainability and bio-degradability*[6]*"* (NanoMarkets report , January 2013)
- *"The EuPC is concerned by statements that bio-based plastic shopping bags are more sustainable than oil-based alternatives. Bioplastics are not a solution to marine litter*[7]*."* The EuPC is the EU-level trade association representing European plastics converters.

Even these five quotes suggest the main interested parties (Figure 1). A little further research gives the following list.

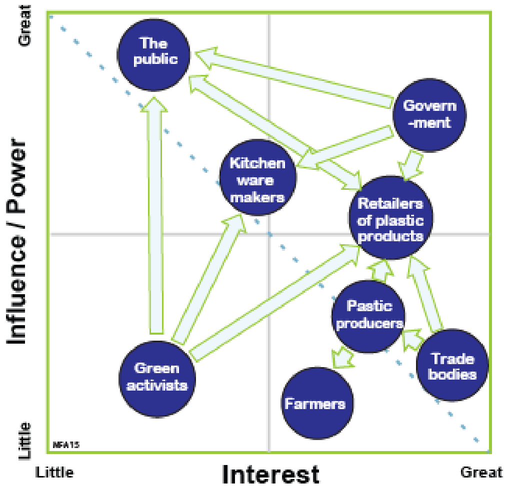


Figure 1. Stakeholders and influence

[3] www.biomasspackaging.com/education/bioplastics/
[4] www.guardian.co.uk/environment/2008/apr/26/waste.pollution
[5] www.thingsaregood.com/tag/bioplastics/#sthh.SJYD8jYY.dpuf
[6] http://nanomarkets.net/blog/article/regulatory_drivers_for_the_bio_plastics_market
[7] www.europeanplasticsnews.com/subscriber/newscat2.html?cat=1&channel=620&id=3594

Table 1. Stakeholders and their concerns

Stakeholders	Concerns
Government	Biofuels and bio-polymers as ways of reducing dependence on oil and reducing carbon emissions[8] and polymer pollution meet national targets
Molders of polymer products	Bio-polymers have inferior properties and are more difficult to process than oil-based plastics
Polymer producers	Bio-polymers seen as a growing and potentially profitable market provided ordinary consumers can be persuaded to choose them
Farmers	Profit by diverting farm production to crops for biofuels and bioplastics[9].
Food packaging industry, supermarkets and retailers	A survey[10]. of their concerns listed "Sustainability", "Economy" and "Product value promise (aesthetics and perception)" as the three most important.
Green campaigners[11]	Fear that the increased use of bio-polymers will contribute to the global food crisis by diverting fertile land from food to bio-polymer-feedstock production.
Consumer associations	Alarm at overstated claims of "greenness", lack of truth in advertising.
Concerned public	Perceived need to reduce oil-dependence for geopolitical and economic reasons and to reduce polymer pollution – the accumulation of waste plastic.

What facts will we need? The stakeholder concerns raise a number of issues***.***

- Are the bio-polymer properties and processability as good as those of oil-based plastics?
- Will bio-polymer production conflict with the production of food and feedstock?
- Can bio-polymers reduce dependence on fossil hydrocarbons and reduce carbon emission?
- Can bio-polymers help reduce polymer pollution?
- Are the claims made by advocates of biopolymers justified?

These provide the starting point for the next step: fact-finding.

Step 3: Fact finding

What information is needed to support or refute the claims made for bio-polymers and the concerns expressed about them? What additional facts do we need for a rational discussion of the proposal? No judgements yet; just facts.

[8] https://bioenergy.ornl.gov/main.aspx
[9] https://bioenergy.ornl.gov/main.aspx
[10] Kingsland, C. (2010) " PLA: A critical analysis" *Packaging Digest* www.iopp.org/files/public/KingslandCaseyMohawk.pdf
[11] http://www.guardian.co.uk/environment/2008/apr/26/waste.pollution.

Materials. A web-search a search of the CES Sustainability database identifies commercially-available bio-polymers (Table 2, left hand side). Competing oil-based polymers are listed on the right. Not all bio-polymers are biodegradable. Those that are, are starred (*)

Table 2. Bio-polymers and commodity oil-based polymers

● **Bio-polymers**	● **Oil-based polymers**
Bio-PP (made from ethanol)	PP Polypropylene
Bio PE (made from ethanol)	PE Polyethylene
PLA Polylactic acid*	Polyvinylchloride
PHA Polyhydroxyalkanoate*	Polyurethane
PTT Polytrimethylene terephthalate	PET Polyethylene terephthalate
CA Cellulose acetate	PS Polystyrene
PA11 Nylon 11	PA6 Nylon 6
TPS Thermoplastic starch*	PCL Polycaprolactone*

**PLA, PHA, TPS, PCL and blends of these with PE, PP and PET are bio-degradable*

The global production of all plastics in 2014 was 299 m tonnes, growing at 3.9% per year; thus the expected production in 2020 is about 400 m tonnes. Almost all are derived from oil, consuming about 5% of global oil production. The global production of bio-plastic in the same year was a little over 1.6 million tonnes[12], or 0.5% of total plastic production. The strongest growth is expected in non-biodegradable bio-plastics, especially the so-called 'drop-in' solutions (bio-based versions of bulk plastics like PE and PET, that merely differ from their conventional counterparts in having a renewable-material base).

If biopolymers are to compete successfully with oil-based plastics they must not only be greener but have comparable properties and price. How do these compare? Figure 3 shows two mechanical properties, Young's modulus and Tensile strength, each plotted against density. (The data shown here are for unfilled, moulding-grade materials.) Bio-polymers, generally, have stiffness and strengths that are comparable with those of PE or PP, but they are heavier, giving them less good values of stiffness and strength per unit weight. Bio-polymers have low heat resistance and poor impact resistance, both of which can be improved with plastizers and by blending with oil-based plastics, but this inhibits recycling.

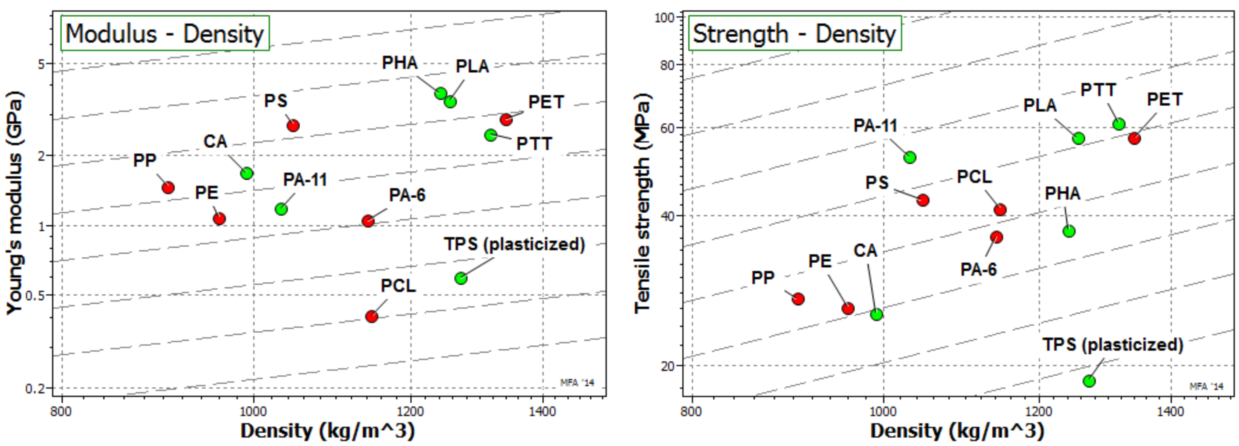


Figure 3. The mechanical properties of oil and bio-based polymers. (CES EduPack 2015)

[12] http://en.european-bioplastics.org/market/market-development/production-capacity/

Bio-polymers are more difficult to mold than oil-based polymers because of the narrow window between the processing temperature and the decomposition point[13]. It is practical to make film, rigid packaging and small (up to 250 grams) injection molded parts, but larger parts are problematic.

Feedstock supply and land area. The land area required to synthesize conventional polymers is negligible; that for bio-polymers is large. The predominant feedstock for bio-polymer production is corn. Growing 1 kg of corn per year requires roughly 1.25 m^2 of fertile land. It takes 3 kg of corn to make 1 kg of ethanol. It takes 2 kg of ethanol to make 1 kg of polyethylene. Thus it takes 7.5 m^2 of fertile land area to make 1 kg of bio-polyethylene per year. At that level the production of 1 million tonnes of bio-polymer per year uses 7,500 km^2 of fertile land; 12 million tonnes needs 90,000 km^2.

Energy. Figure 4 compares the embodied energy[14] per unit volume of bio-polymers and oil-based plastics. There is very little difference between them – only starch-based polymers (TPS) are significantly lower. At first sight it seems surprising that a polymer based on natural materials is nearly as energy-intensive as one made from oil. It is because the fermentation or processing needed to make bio-resins requires heat and thus carries an energy and carbon burden, and the subsequent polymerization step for bio and oil-based polymers makes almost identical contributions to both.

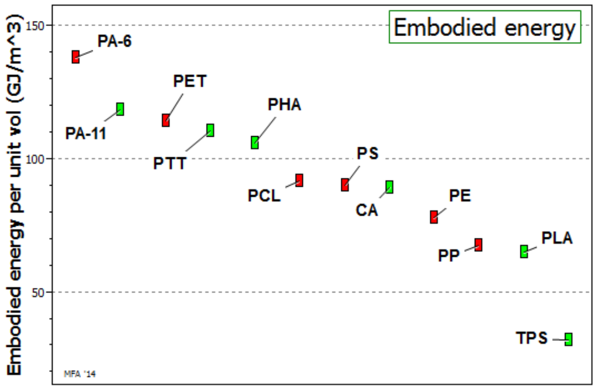


Figure 4. The embodied energy of oil-based polymers (red) and bio-polymers (green). (Chart made with the CES EduPack 2015).

Energy, Carbon footprint and Environment. Bio-polymers are widely perceived to have a better eco-character than oil-derived polymers, but evidence does not entirely bear this out. Figure 5 (a) shows the carbon footprint of bio and oil-based polymers. Today's bio-polymers compare poorly with conventional oil-based alternatives. Figure 5 (b) shows a comparison of the water requirement associated with producing bio and conventional polymers. The water demand of bio-polymers is high because of the needs of the plant or animal feedstock from which they are derived.

What about polymer pollution? Some bio-polymers bio-degrade in the true sense of returning their constituent to the bio-sphere in the form from which they were first drawn. But not all. More than half the present day production is "drop-in" bio-polymers (those identical in chemistry with oil-based plastics) such as bio-PE, and these, of course, do not bio-degrade.

[13] http://www.ptonline.com/articles/injection-molding-bio-polymers-how-to-process-renewable-resins

[14] The "embodied energy" of an oil-polymer includes both the energy required to synthesize it from oil and the energy content of the oil itself (roughly 44 MJ/kg).

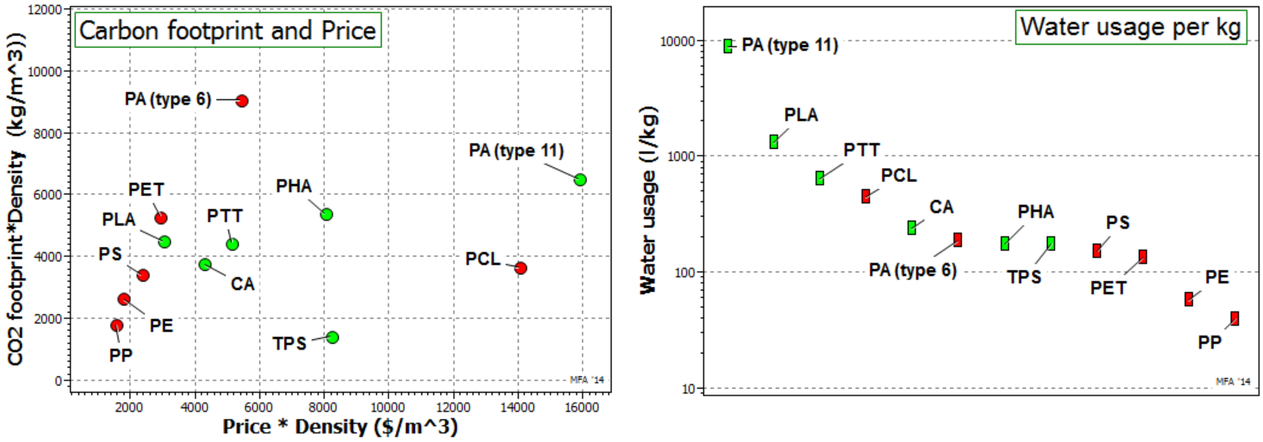


Figure 5 (a) The carbon footprint of commodity oil base polymers (red) and bio-polymers (green). (b) Water usage in making the same polymers, segregated into those that are biodegradable and those that are not (CES EduPack 2015)

Legislation. The largest use of bioplastics is in packaging, particularly that for food. Most nations have legislation that controls aspects of the packaging industry. Much of it seeks to encourage recycling and the use of bio-degradable or compostable materials, providing incentives to use the bioplastics that meet these criteria. Here are two examples.

- EU Packaging Directive 94/62/EC, which urges the use of bio-degradable or compostable packaging.
- EU Registration, Evaluation, Authorization and Restriction of Chemical Substances Directive EC 1907/2006 (REACH) that prohibits the use of certain plasticizers and flame retardants in plastics.

It is important to be aware of legislation like these when considering the use of new materials.

Economics. Commodity plastics (PP, PE, PVC, PET, PS) all have prices between \$1.5 and \$2.8 per kg, Bio-polymer, today, cost more than that. Figure 6 plots the price per kg against density on the left, and the price per unit volume (per m^3) on the right. In a straight substitution of a bio-polymer for a conventional polymer, it is the price per unit volume that is significant. PLA is about 25% more expensive per unit volume than PP, PE or PS. All the other bio-polymers are more expensive than this.

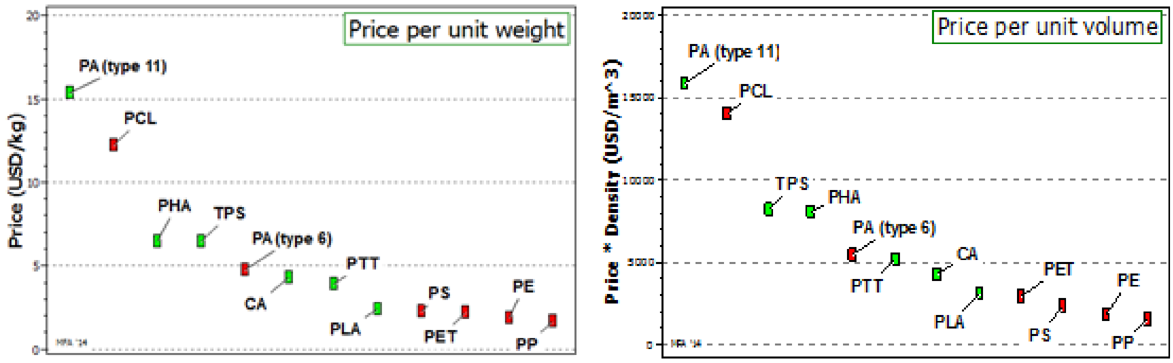


Figure 6. The price per kg and the price per m^3 of oil-base polymers (red), and bio-polymers (green). (CES EduPack 2015)

Society. A sustainable development must gain public acceptance. Market appeal is partly a question of what one stakeholder called “product value promise”. Cellulose acetate and PLA are available in grades with high clarity and gloss that make for attractive food packaging, and the association with environmental stewardship by severing the link with petrochemicals and offering biodegradability has emotional appeal. However, some bio-polymers have a smell that makes them less appealing for durable products such as car interiors.

Summary of significant facts

- *Bio-polymer properties are comparable with those of oil-based plastics but they are more difficult to process.*
- *Bio-polymer production on a significant scale from cultivated crops requires a large area of fertile land.*
- *Bio-polymers are, at this point, more expensive than PE, PP, PS or PET.*
- *Bio-polymers have a lower carbon footprint than oil-based polymers, but not by much.*
- *Some bio-polymers are bio-degradable, but not all. The ability of bio-polymers to reduce polymer pollution has sometimes been overstated.*

All the charts in this section were made with the CES EduPack 2015 software (www.grantadesign.com).

Step 4: Forming a judgement

What impact do the facts have on the three capitals? There is no single answer to this question; the weight given to the facts depends on values, culture, beliefs and ethics. Here we present one view. The main points are summarized in Figure 7.

Natural capital.

- *Reduced dependence on fossil hydrocarbons*? Polymer production uses about 4% of the global production of fossil hydrocarbons. Replacing 3% of this by bio-polymers reduces demand by 0.12%. Even the ideal of 30% replacement reduces the demand by just 1.2%. So – yes, but not much.

- *Reduced carbon emission?* The carbon footprint of bio-polymers is marginally different from that of oil-based polymers. There is no evidence, at present, that bio-polymers make a significant difference.

- *Conflict with the production of food and animal feedstock?* The potentially usable arable land area of the earth is about 31 million square km[15]. Making 12 million tonnes of biopolymers annually from cultivated feedstock (rather than waste) needs an area of 90,000 km^2, about twice the area of the Netherland or the State of Massachusetts. This is 0.3% of global productive land area, or 6% of US productive land, or 9% of that of Europe.

[15] https://en.wikipedia.org/wiki/Arable_land

- *Will bio-polymers help reduce polymer pollution?* Some bio-polymers can bio-degrade but land-fill sites are anaerobic, inhibiting the breakdown processes. Thus biodegradability may reduce polymer pollution at sea or in the countryside, but it will not reduce the volume of plastic in landfill.

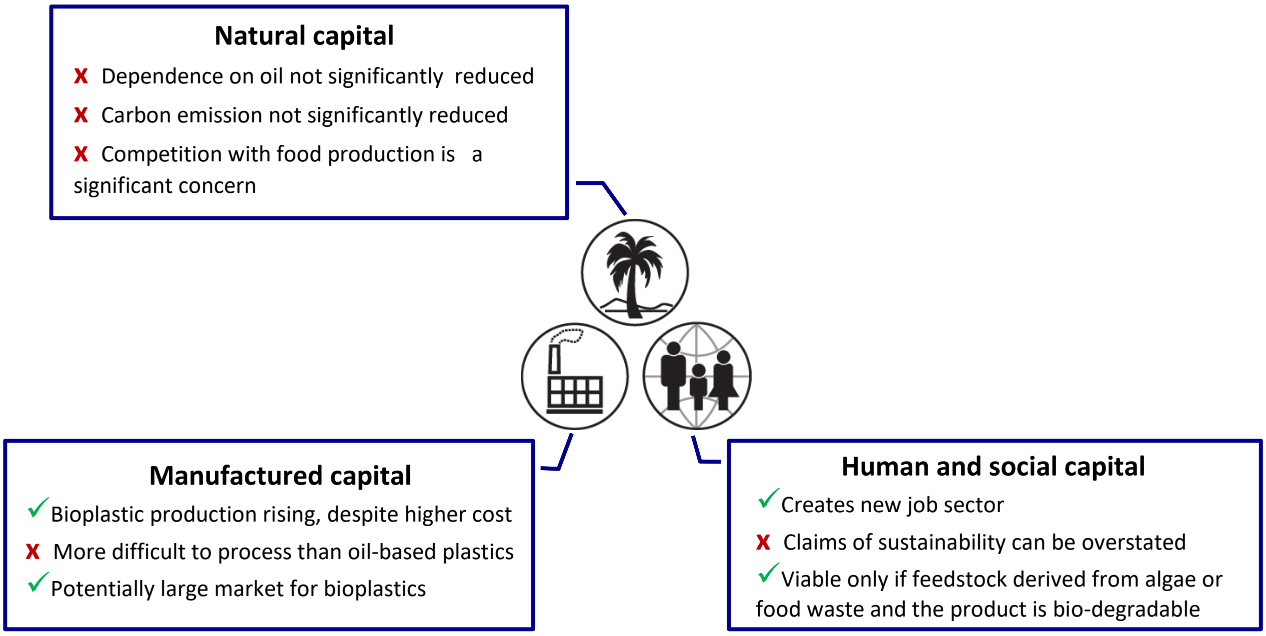


Figure 7. Synthesis – debating the impact of the facts on the three capitals. Check-lists help with this and the other steps.

Manufactured and Financial capital

- *Are bio-polymers financially viable?* Basing them on natural feedstock decouples their price from that of oil, but links it to that of commodities such as corn, the price of which also fluctuates with growing conditions and with market forces. Despite their higher price at present, the bioplastics market is growing at 8-10% per year and is predicted by some studies to take up to 25% of the polymer market by 2020[16].

- *Is the processability of bio-polymers as good as those that are oil*-based ? Some bio-polymers – those synthesised from bio-alcohols (bio-PE for example) – are identical to their oil-based equivalents. Others are more difficult to process.

Human and Social capital

- *Personal satisfaction.* The interaction with Human Capital is psychological rather than real. Bio-polymers, to some, offer a significant emotional satisfaction in relying on renewable feedstock rather than fossil hydrocarbons

[16] www.hkc22.com/bioplastics.html

- *New industries*[17]. The availability of new materials (the bio-polymers) could stimulate new industries (such as 3-D printing of polymer products) in land-rich, oil-poor countries.

- *Are the public accurately informed?* There are indications[18] that the market for bio-polymers is sustained by overstated claims for their sustainability. Building social capital depends on trust made possible by responsible public information.

Step 5: reflection

Short term.

Can the Prime Objective be met? The current (2014) production of bio-polymers is about 1 m tonne/year. Expanding it to the target of 12 m tonnes/year by 2020 means a growth rate of about 25% per year. This is twice the current growth rate of bio-polymer production (10 – 12% per year) but is not impossible.

Do bio-polymers cut carbon emissions or reduce plastic waste? Not significantly. Bio-polymer production is, of course, in its infancy; as production is scaled up and processing is refined it is expected that bio-polymers will begin to show an environmental gain.

The economics: the present "favourite child" status of bio-polymers allows an expanding market even though they cost more than oil based plastics, but research, development and scale-up is expected to make them cheaper and the rising cost of petrochemicals may disadvantage oil-based plastics. The advantage may be lost if the competition for land and water to grow the feedstock for bio-polymers drives up commodity prices. And there is the uncertainty about supply – a poor growing season can halve the yield per hectare.

The evidence suggests that the goal of increasing global production to 12 m tonnes of bio-polymers per year is achievable. But it is buoyed up, for now, by an emotional response from the public and from government to our disquieting dependence on fossil hydrocarbons and the seeming purity of a dependence, instead, on nature. Making this a sustainable development in the short term depends on investment and trust.

Longer term.

Three issues will bite if bio-polymer are to replace oil-based plastics on a significant (10% or more) scale; their price, their more limited range of properties and processability and their competition for resources with food production. In a world with many people without adequate food and water, diverting these to polymer production does not seem right. Could this not be overcome by seeking and alternative feedstock? There are at least three potential sources that do not compete with food: agricultural waste, food waste and cultivated marine algae.

Agriculture is the world's greatest industry and it produces waste on a corresponding scale. This waste could, potentially, eliminate the need for land and water for bio-polymers. The global production of straw, for example, is comparable with that of grain. The challenge is to find ways to make it into a feedstock for the polymer industry[19].

[17] http://www.3ders.org/articles/20120208-developing-sustainable-bioplastics-for-3d-printers.html
[18] www.europeanplasticsnews.com/subscriber/newscat2.html?cat=1&channel=620&id=3594
[19] One of many sources: http://www.worldchanging.com/archives/004756.html.

Marine algae[20] require only seawater, sunlight, carbon dioxide and nutrients to flourish, leaving fresh water and land for food production. Algae multiply fast, producing up to 15 times more organic matter per unit area than land biomass. Fermenting them to make ethanol and other alcohols could allow synthesis of bio-polyethylene, bio-PVC and bio-EVA.

Success in reaching the destination of this proposal appears to lie in investment in research and development in these two branches of bio-technology.

Further reading

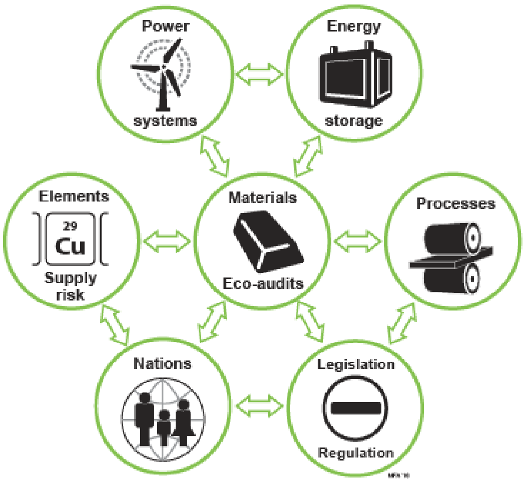
Wool, R.P. and Sun, X. S. (2005) "Bio-based polymers and composites", Elsevier, Amsterdam, Netherlands. ISBN 0-12-763952-7. (*A text introducing the chemistry and production of bio-polymers*.)

[20] Here is one (of many) sources. http://www.sciencedaily.com/releases/2012/10/121015084649.htm

Sustainable Development Teaching Resources

Resources

- *Granta Teaching Resource Package: Assessing sustainable developments – a tool kit*
- *PowerPoint presentations*
- *Explanatory handouts*
- *Templates*
- *Micro-projects*



Case studies

- *Greener beer cans*
- *Bioplastic or polyprop?*
- *Electric cars*
- *Electric buses*
- *Which hand dryer?*
- *Plastic books*
- *Wind farms*
- *Low carbon concrete*

The CES EduPack Sustainable Development Edition

The Sustainability Database is a fact-finding tool to introduce students to the complexity of decision-making for sustainability. It helps contextualize the role of materials and it expands competences in critical thinking about complex issues (including resource use, legal barriers, ethical considerations, societal and economic concerns). The individual data-tables are explained in Section 3 of this Teaching Resource Package.

The book "Materials and Sustainable Development" (ISBN-13: 978-0081001769) describes this method and its applications in more detail.

Authors. Professor Mike Ashby and Education Division team at Granta Design Ltd. www.grantadesign.com/education

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