Sustainability Case Study

Scaling up bio-plastic production

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Summary

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.

This resource is complementing Active-Learning Tool Kit Sustainable Development (available on AER webpage) and is an example of application for Ashby's 5-step methodology.

Note: The original creation of this resource was in 2017. The updates are made in line with a case study, described in the 2d edition of M. Ashby's textbook "Materials and Sustainable Development".
All references (including links) were accessed during 2023.

Table of Contents

Scaling up bio-plastic production -- Handout

The proposal

Commodity plastics are made from fossil hydrocarbons, particularly oil. About 5% of global oil and gas production is used for making plastics, 390 million tons of it in 2021 and growing 4% per year[1]. 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). The global production of bio-based plastics in 2021 was 2.4 million tonnes, growing at 16% per year[2].

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.

According to a white paper on sustainability cited by Bio-plastics magazine, 28 July 2020 [3]"The major benefit of bio-based plastics is that they reduce our dependence on fossil resources and, contrary to fossil-based plastics, are climate-neutral. Between 85 and 90% of all fossil-based plastics could easily be replaced by bio-based plastic". That is a proposal for sustainable development. Are the claims valid? Would replacing oil-based plastics with bio-plastics be a sustainable development? Who are the interested parties? Is it practical to replace even half of the present-day plastic production with bio-plastics within the time frame of UN sustainable development goals, meaning by 2030? Can we form a balanced opinion about the claim?

The Methodology

This resource follows the five-step methodology, which is simply explained below and explained in detail elsewhere (see, for instance, Active-Learning Tool Kit Sustainable Development in open access available on Ansys Education Resources).

- What is the prime objective? What is its scale and timing? What is the functional unit?

[1] https://www.statista.com/statistics/282732/global-production-of-plastics-since-1950/
[2] Global bioplastics production will more than triple within the next five years – European Bioplastics e.V. (european-bioplastics.org)
[3] https://www.bioplasticsmagazine.com/en/news/meldungen/20200728Towards-a-future-with-bioplastics.php

- Who are the stakeholders and what are their concerns?
- What facts will be needed to enable a rational discussion of the proposal?
- What, in your judgment, is the impact of these facts on Natural, Manufactured, and Social Capitals?
- Is the proposal a sustainable development? Could the objective be better met in other ways?

In terms of decision making, the decisions, following this methodology, are more systematic and objective until we get all the facts collected. After this, there is more a value-based subjective approach to assess impacts and to have a final reflection on suggested proposal of sustainable development (see Figure 1).

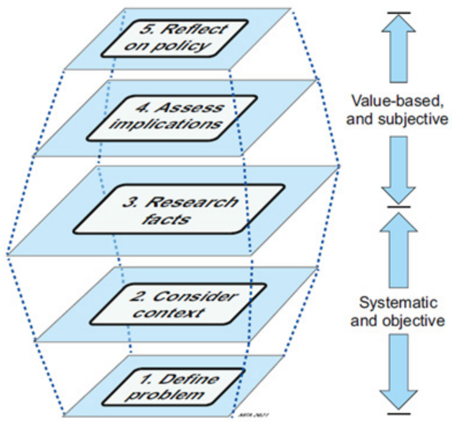

Figure 1. Schematic representation of the 5-step methodology from Ashby M. (2022)[4]

Where can Ansys Granta EduPack help with Fact Finding?

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

The **Regulations data-table (Level 3 Sustainability)** identifies government incentives and restrictions that relate, for instance, to packaging, waste, and the use of chemicals.

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

[4] Materials and Sustainable Development - 2nd Edition (elsevier.com)

The **Nations of the world data-table (Level 3 Sustainability)** provides background on the prosperity, environmental performance, and governance of countries from which feedstock for bio-polymers might be sourced or where bio-polymer production is located[5].

The **Graph facility of Ansys Granta EduPack** allows data to be plotted as property charts, annotated and saved to Word Documents.

Scaling up bio-plastic production - Example of Assessment

The number of the sections corresponds to that of the 5 steps of the analysis. Ansys Granta EduPack databases help with fact-finding in ways described in this case study.

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

- **Objective**: to reduce fossil fuel consumption and greenhouse gas emission by replacing oil-based plastics with those based on bio-feedstock.
- **Size scale**: 50% of current plastic production, meaning 195 million tonnes per year
- **Time scale**: by 2030
- **Context**: Developed nations (North and South America, Europe)
- **Functional unit**: 1 kg of plastic.

Step 2: stakeholders and their concerns

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

- "UK government launches bio-plastics drive. The department for business, energy and industrial strategy (BEIS) has announced a drive to encourage innovation in bio-plastics ." (Resource magazine, 22 July 2019)[6]
- "Co-op supermarkets will replace all single use plastic bags with biodegradable alternatives " (bio-plastic news, 24 September 2018)[7]
- "With dwindling fossil resources and the need for more cost and fuel effective vehicles, bio-plastics are hailed as one of the best replacement materials for bio-plastics and metals (in cars) " (Thomasnet, 26 February 2020)[8]
- "It's not food or bio-plastics. It's food AND bio-plastics. Only 0.01% of global agricultural area is used to grow feedstock for bio-plastics, compare to 98% used for food, feed, and pastures " (Natureworks, makers of Ingeo PLA, a biodegradable bio-plastic)[9]

Even these four quotes suggest the main interested parties (Figure 2).

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[5] Additionally, one can use the Social Impact Audit Tool (prototype) to explore potential social hotspots (negative or positive impact). Available by request from Academic Development team academic@ansys.com and described in a Paper: Social Life-Cycle Assessment and Social Impact Audit Tool www.ansys.com

[6] https://resource.co/article/uk-government-launches-bioplastics-drive

[7] https://bioplasticsnews.com/2018/09/24/co-op-supermarkets-use-bioplastics-bags/

[8] https://www.thomasnet.com/insights/do-bioplastics-have-a-place-in-automotive-manufacturing/

[9] https://www.natureworksllc.com/~/media/Files/NatureWorks/What-is-Ingeo/Where-Ingeo-Comes-From/NatureWorks_Ingeo_food-and-bioplastics_pdf.pdf?la=en

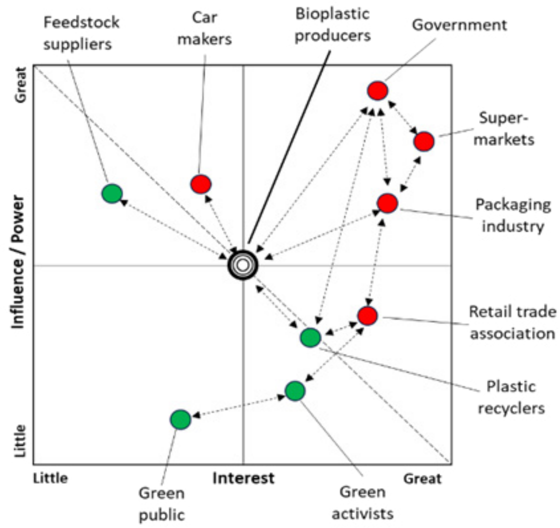

Figure 2: Stakeholders and Influence

A little further research gives the following list.

Table 1: Stakeholders and their concerns

Stakeholders	Concerns
Government	Bio-fuels and bio-polymers as a way of reducing dependence on oil and reducing carbon emissions[10] 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 are growing and potentially profitable market provided ordinary consumers can be persuaded to choose them
Farmers	Profit by diverting farm production to crops for bio-fuels and bioplastics[11]
Food packaging industry, supermarkets, and retailers	A survey[12] of their concerns listed "Sustainability", "Economy", and "Product value promise (aesthetics and perception)" as the three most important
Green campaigners[13]	Fear that increased use in 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
Car makers	Using bio-plastics for non-load-bearing components demonstrates commitment to eco-friendly design
Trade associations	Promotion of bio-plastics and bio-based plastics, informing consumers and challenging misconceptions about them

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

The stakeholder concerns raise several issues. What facts will we need?

- Are the bio-plastics properties and processability as good as those of oil-based plastics?
- Will bio-plastics production conflict with that of food?
- Can bio-plastics reduce dependence on fossil hydrocarbons and reduce carbon emission?
- Can bio-plastics help reduce polymer pollution?
- Are the claims made by advocates of bio-polymers 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-plastics and the concerns expressed about them? What additional facts do we need for a rational discussion of the proposal? No judgments yet; just facts.

Materials A search in the Granta EduPack Sustainability database lvl2 identifies some of the commercially available bio-plastics (Table 2, left hand side). Competing oil-based polymers are listed on the right. Not all bio-plastics are biodegradable. Those, that are, have been 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 bio-plastics production is set to increase significantly from around 2.4 million tonnes in 2021 to 7.5 million tonnes in 2026[14]. This is still a fraction compared to the overall production of plastics globally, which was estimated at 390.7 million metric tons in 2021 (4% annual increase)[15].

Materials performance: mechanical properties If bio-polymers 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 property groups: the specific stiffness E/ρ ¬and specific strength σ_y/ρ, where E is Young's modulus, σ_y is the yield strength and ρ is the density. It shows that bio-plastics have mechanical properties that are broadly comparable with those of conventional PET or PP.

[14] Global bioplastics production will more than triple within the next five years – European Bioplastics e.V. (european-bioplastics.org)
[15] Plastic production worldwide 2021 | Statista

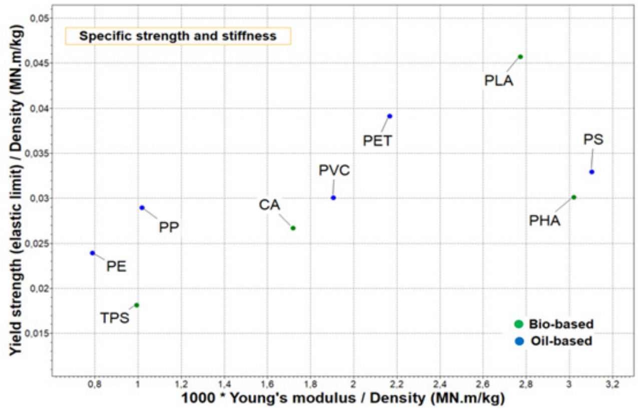

Figure 3: The mechanical properties of oil and bio-based polymers
(made with Ansys Granta EduPack 2023 R1)

Bio-polymers are more difficult to mold than oil-based polymers because of the narrow window between the processing temperature and the decomposition point. 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. At present, 0.6% of plastic production is bio-plastic. If half of all oil-based plastic production is replaced by bio-plastic by 2030, production will have to grow at 68% per year. The land area required to synthesize conventional polymers is negligible; that for bio-polymers is large. It takes 3 m2 of fertile land area to grow the feedstock for 1 kg of bio-polyethylene per year. At that level, today's bio-plastic production (2.4 million tonnes/year) needs 7,200 km2 of productive land. The equivalent value for 195 million tonnes per year (half of all plastic production) is 585,000 km2. There is 47 million km2 of productive agricultural land in the world. About one-third of this is used to grow crops so producing bio-plastic today takes only 0.04% of crop-bearing land. If the proposal is realized, this rises 3.7%. To give some perspective the area of the Netherlands is 41,500 km2 but only a part, 23,000km2, is designated as agricultural. Replacing half of oil-based plastic by bio-plastics needs 25 Netherlands.

Environment: carbon footprint and water usage. Bio-polymers are widely perceived to have a better eco-character than oil-derived polymers, but evidence does not entirely bear this out.

Figure 4 (a) shows the carbon footprint of bio and oil-based polymers.
TPS and PHA do better than oil-based PP or PE but the others don't. At first sight it seems surprising that a plastic-based on natural materials is nearly as carbon-intensive as one made from oil. It is because the harvesting, fermentation or processing needed to make bio-resins takes energy and has an associated carbon burden, and the subsequent polymerization step for bio and oil-based plastics are essentially identical.

Figure 4 (b) compares the water needed to make 1 kg of bio and conventional plastics.
The water demand of most bio-plastics is high because the sugar cane, corn, or soya used as feedstock requires irrigation.

What about polymer pollution? Some bio-polymers bio-degrade in the true sense of returning their constituent to the biosphere 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.

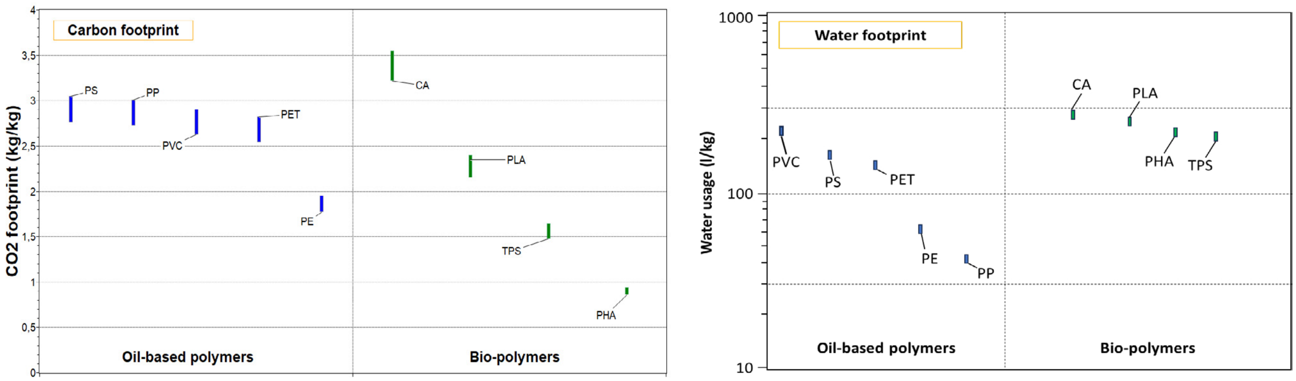

Figure 4:
(a) The carbon footprint (blue) and bio-polymers (green) (Ansys Granta EduPack 2023 R1) and (b) Water usage in making of commodity oil base polymers (graph created in reference to [Materials and Sustainable Development - 2nd Edition (elsevier.com)])

Legislation. The largest use of bio-plastics 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 bio-plastics that meet these criteria. Here are two examples.

- EU Packaging Directive 94/62/EC, which urges the use of bio-degradable or compostable packaging (revised in 2018 more ambitious targets for recycling of packaging waste)
- 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 the above when considering the use of new materials.

Economics. Commodity plastics (PP, PE, PVC, PET, PS) all have prices between $1.4 and $2.5 per kg, Bio-polymer, today, cost more than that (Figure 5). In a straight substitution of a bio-plastic for a conventional polymer, it is the price per unit volume rather than per unit weight that is significant, but since all these plastics have almost the same density, the conclusion is the same.

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

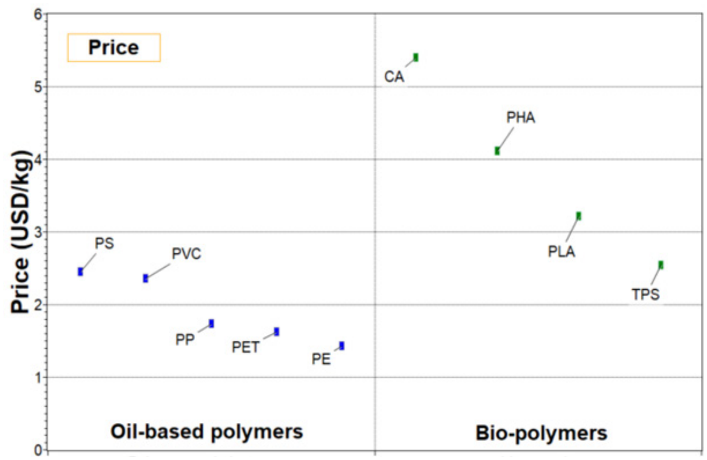

Figure 5: The price per kg of oil-based polymers (blue), and bio-polymers (green). (Ansys Granta EduPack 2023 R1)

Society. Sustainable development proposals 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. Brazil has become a major producer of bio-plastics and biofuels[16] based on sugarcane ethanol, bringing employment and social benefits to poorer parts of the country.

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, and are more difficult to recycle
- Bio-polymers have a lower carbon footprint than oil-based polymers, but not by much.
- Some bio-polymers are bio-degradable, but not all.

Step 4: forming a judgment

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, which main points are then summarized in Figure 6.

[16]Revision of Directive 94/62/EC on packaging and packaging waste | Think Tank | European Parliament (europa.eu)

Natural Capital.

- *Reduced dependence on fossil hydrocarbons?* Polymer production uses 5% of the oil production per year. Replacing half of this with bio-plastics reduces demand for oil by 2.5%, but with many associated difficulties. Transport, heating, and the generation of electricity use 83% of oil and gas production. A small change there could have a much bigger effect.
- *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.
- *Is water a concern?* Growing irrigated arable plants as feedstock for bio-plastics consumes much more water than that used to synthesize PE or PP from oil (Figure 4(b)). Access to freshwater is already a concern in many parts of the world. Expanding technologies that increase demand can only make it worse. Where water is plentiful, that problem does not arise.
- *Conflict with the production of food and animal feedstock?* The land area needed to supply today's bio-plastics output is tiny in comparison with that used for food and pasture. Making half of all plastic from
- Cultivated bio-feedstock creates a problem; co-opting 3.7% of productive arable land to make plastics when there is a global shortage of food does not seem right. Research into using agricultural and food waste or marine algae instead could provide a solution.
- *Will bio-polymers help reduce polymer pollution?* Most oil-based plastics and 'drop-in' bio-based equivalents don't biodegrade. Expanding today's menu of bio-plastics to the desired 195 million tonnes per year would mean 25% of all plastic could biodegrade. Eliminating plastic pollution will need more than that.

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 bio-plastics market is growing at 15% per year.
- *Is the processability of bio-polymers as good as those that are oil-based?* Some bio-polymers – those synthesized from bio-alcohols (bio-PE for example) – are identical to their oil-based equivalents. Others are more difficult to process. The size limit on injection moldings, mentioned earlier, is a problem
- Oil and bio-plastics can't be mixed for recycling, creating a problem for the recycling industry.

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
- *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.

[17] http://www.3ders.org/articles/20120208-developing-sustainable-bioplastics-for-3d-printers.html

- *Public misconceptions.* The value-added when oil derivatives are polymerized to plastic is greater than when it is refined for fuels. The carbon in plastics is trapped until the end-of-life of the product containing it, which can be long (the average automobile lasts 12 years) whereas that in fuels is dumped into the atmosphere as soon as it is used. Bio-plastics are frequently promoted as sustainable, carbon-neutral, oil-free, biodegradable replacements for those based on oil – the proposal with which this case study started is an example. The facts suggest that little of this is entirely true. Social capital is built on trust; this is only made possible by responsible public information.

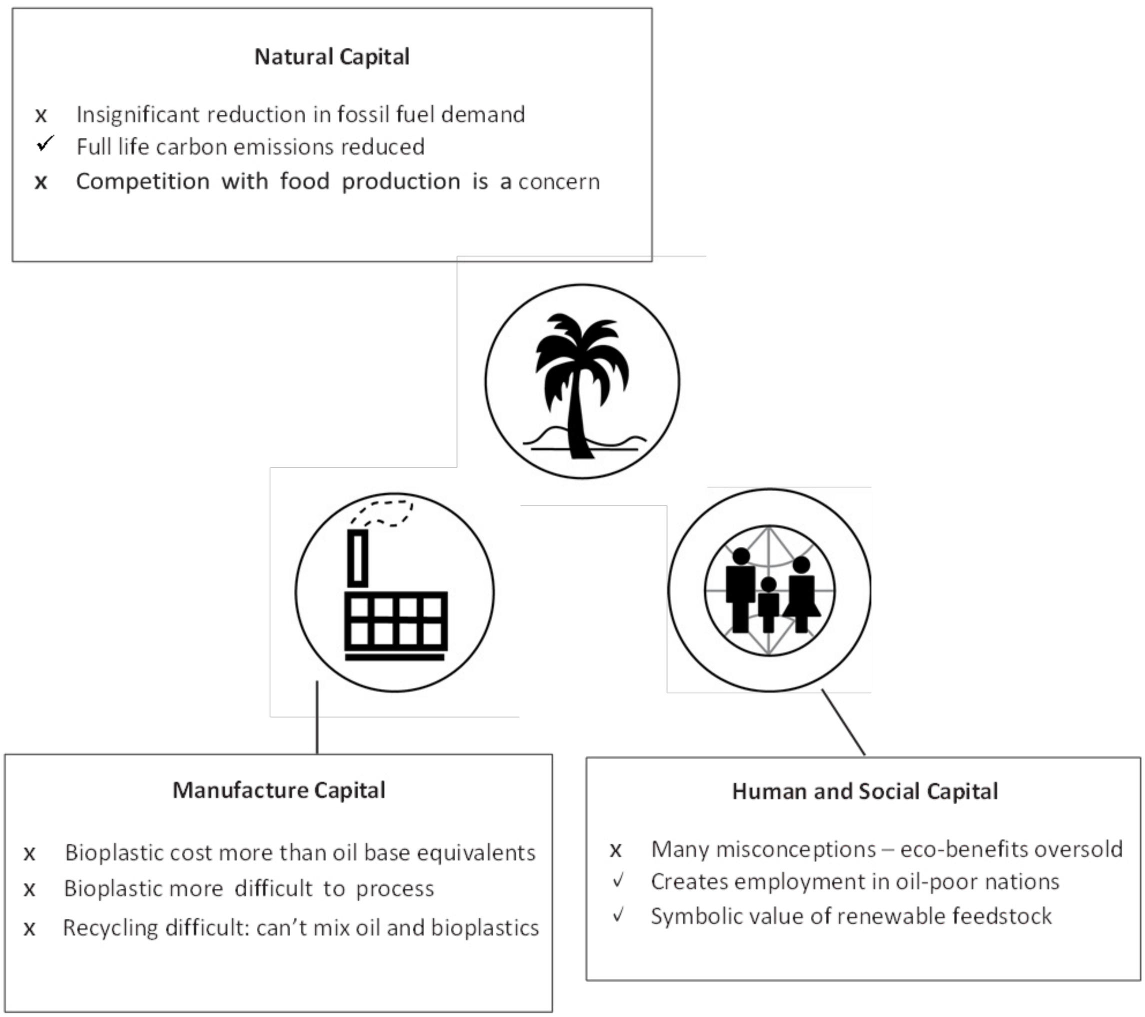

Figure 6. Synthesis – debating the impact of the facts on the three capitals. Check-lists help with this and the other steps.

Step 5: reflection

Short term – 1 to 10-year time frame

Can the objective be met?

The 2021 production of bio-plastics was about 2.4 m tonne/year, the proposal suggests an increase to 195 tonnes/year by 2030 – this is 80 times of current production level.
Do bio-plastics cut carbon emissions or reduce plastic waste? For single-use short-lived products that are not recycled, yes. Plastic products with long lives sequester carbon and, if recycled, continue to do so whether oil or bio-based. Bio-degradation can reduce plastic waste significantly only if all, or almost all, plastics biodegrade.

Long term – 10 to 50-year time frame

Three issues will bite if bio-polymer are to replace oil-based plastics on a significant (50% 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 an 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.

Roughly one-third of the food produced in the world for human consumption every year – approximately 1.3 billion tonnes – is lost or wasted[18]. This, and the inedible waste product of agriculture (straw, for example) are a potential source of feedstock for bio-plastics. Finding an economic way to do this would strengthen the case for bio-plastics greatly.

Marine algae[19] 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 branches of bio-technology.

[18] https://www.fao.org/save-food/resources/en/
[19] Here is one (of many) sources. http://www.sciencedaily.com/releases/2012/10/121015084649.htm

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