Sustainability: Getting everyone involved

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Abstract

Humanity is currently using the Earth's resources at a much higher rate than that at which the planet can regenerate them. Public awareness of this problem is increasing, especially with regard to issues such as the need to recycle waste, and to reduce our reliance on single-use plastic and on fossil fuels. However, the scale of the problem is still under-appreciated, and in many cases, there are no simple solutions to make our current systems truly sustainable. Meanwhile, the global human population is growing and despite higher awareness, our consumption of global resources is increasing rather than decreasing. This article explores some of the reasons why sustainability is such a complex problem and puts the case that an effective approach to sustainability will require effort from experts in fields ranging from economics to materials chemistry, as well as from legislators and leaders of industry.

Keywords: sustainability; circular economy; Life Cycle Analysis; recycling

Introduction

> *The only way forward, if we are going to improve the quality of the environment, is to get everybody involved.* Richard Rogers, Architect (1933-2021)

Communities of human beings have always faced concerns about whether their lifestyle can be maintained. It is likely that even our distant ancestors worried about what would happen if they ran out of prey or water. However, the scale of our modern-day requirements dwarfs that of palaeolithic communities; the global population recently surpassed 8 billion individuals (**Sadigov, 2022**). We also have a tendency to expect improvements in lifestyle over time- this is particularly the case in developed nations. In his 1982 book *Overshoot*, (**Catton, 1982**) William Catton wrote that '*Human population, organised into industrial societies … responded by increasing more exuberantly than ever, even though this meant overshooting the number our planet could permanently support'. It is now clear that we have passed the point of an ecological 'overshoot*', i.e., a point beyond which the planet cannot indefinitely supply our population (**Wackernagel et al., 2002; Fanning et al., 2022**). This concept is illustrated clearly by the Global Footprint Network, a non-profit organisation that generates a yearly estimate for Earth's 'Overshoot Day'. The Overshoot Day is the calendar day by which humans have consumed all of the resources that the Earth is able to regenerate in a year (**Global Footprint Network, 2022**). For 2022, the Overshoot Day was estimated at July 28, and the general trend over the last 3 decades has been for this date to become earlier each year. Even in 2020, the year when large parts of the global economy were effectively brought to a halt by the COVID-19 pandemic, the overshoot date for that year was pushed back only to August 22. This is a remarkable result; even with such an abnormal drop in production and consumption as occurred in 2020, we are still not able to sustainably provide for humanity from the resources that we have. Clearly, small changes in daily lifestyle are not going to effectively address this deficit; more fundamental restructuring of our resource consumption is needed, and any meaningful change is likely to affect all areas of daily life, including food, energy, materials, and healthcare.

Given this assertion, the need to fulfil humanity's needs more sustainably is arguably one of the most 'interdisciplinary' research goals of our current time, touching as it does upon so many areas. The aim of sustainable living goes further than simply making sure the electricity stays on in our houses; it has dramatic implications for the usage of raw materials, land, and water. For sustainability to become a realistic target, all manufacturing processes will ultimately need to be assessed in terms of the way in which resources are used, and waste material disposed of. More fundamentally, we need to discuss what sustainability is, and how it can be measured. Insights from this type of analysis will inform our approach to questions such as *what do we need to improve*, and *how will we know whether we have succeeded*?

In everyday language, if we speak of something being sustained, we mean that it stays the same over time. We need a more nuanced definition than this when discussing environmental issues, however, because humanity's needs are fluid, and the planet is a dynamic system. A number of approaches have been taken to defining sustainability (**Kuhlman & Farrington, 2010; Mensah, 2019; Ruggerio, 2021; Sakalasooriya, 2021**). One of the most well-known arises from a report produced in 1987 by the 'World Commission of Environment and Development' a sub-organisation of the UN; this report became known as the Brundtland report, after the chair of the Commission (**World Commission on Environment and Development, 1987**). The Brundtland report set out a statement that '*Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs*.' While we can certainly be sceptical about the progress that humanity has so far made towards this goal, this statement does provide us with a useful definition; a *sustainable* process is one that we can carry out today, and use indefinitely, without preventing our descendants from using it also if they require it.

The Economics of Sustainability

It is tempting to see sustainable solutions as being rooted in the sciences, with the development of newer and 'greener' technologies and more efficient ways to use resources. This view has some merit, because considerable research effort is currently being expended on this type of research. However, any discussion on a sustainable future should arguably start with the field of economics since our current situation can be described as an increasing human population competing over finite available resources. Resource allocation can be analysed using tools developed in the field of game theory, which is a mathematical construct describing situations where (a) rational decision-makers (termed 'players') compete for outcomes that are beneficial to themselves, and (b) the optimal outcome for an individual player is affected by the decisions made by the other players.

The concepts generated in game theory are applicable to many global environmental problems, including man-made climate change. The current consensus among reputable scientists is that the atmosphere is warming due to carbon dioxide being released by human activities. If all countries co-operated to reduce CO_2 emissions, everyone would benefit as the atmosphere would return to its natural composition. However, there is an upfront cost involved in limiting CO_2 emissions, and for an individual country this may be perceived as more significant than possible future benefits from reducing CO_2 emissions (which will only work if all other countries also co-operate) and so none of the countries involved choose to co-operate. The application of game theory to this type of scenario was described in detail by P. Wood (**2012**). A simple model described by Wood considers two neighbouring countries, A and B, who can make a straightforward decision to 'Continue polluting' or 'Stop polluting'. Numerical values are assigned to each outcome. If both players continue to pollute, the outcome is poor for both, as both have to live with the outcome of pollution, so we allocate a low score for both A and B (1,1). If both choose to stop pollution, then the environment overall improves, so we allocate a higher score for each country (8,8). However, if A chooses to stop polluting while B continues as before, then B benefits from A's action without incurring immediate costs (which will all be borne by A). For this outcome, we allocate a lower score for A and a higher one for B (0,10).

So, what is the most 'rational' decision here for each country? The answer is illustrated by table 1. If A continues to pollute, it gets 1 if B also pollutes and 10 if B stops; however, if A stops polluting, it only gets 0 if B pollutes and 8 if B stops. Therefore, the most 'rational' decision for each country is to continue to pollute, even though if both countries had chosen to stop, they could have achieved a better overall result (8 each). So, despite each player making rational decisions, and having full awareness of the possible outcomes, we still end up with the least 'optimal' result, in that both countries continue to pollute. This is a version of the well-known 'prisoner's dilemma', in which two prisoners held in separate cells must decide independently if they will confess or deny their crime, knowing that their sentence depends on whether their confederate also confesses or denies it.

Figure 1: Simple 'Prisoner's Dilemma' model of pollution consideration between two competing nations (**Wood, 2012**)

		A	
		Pollute	Stop polluting
B	Pollute	(1,1)	(0,10)
	Stop polluting	(10,0)	(8,8)

In the real world, more complex models are required, since in practice there are a range of options (e.g., each country can choose how much to decrease pollution, rather than a straightforward choice between 'pollute' and 'stop polluting') but this simple model illustrates the important principle that when the players act in their own self-interest the results are not optimal for the group. There is ample evidence of this globally- from an overview perspective it seems obvious that countries should decrease carbon emissions, reduce plastic pollution, etc, but countries acting in their own self-interest have so far failed to do so sufficiently to solve the overall sustainability problem.

In a 'prisoners' dilemma', then, both parties engaged in the dilemma tend to lose out in that everyone gets a sub-optimal result. In order to produce a more desirable outcome, the game itself must be changed. In terms of a global environmental issue such as the effort to limit climate change resulting from carbon dioxide emissions, the players (nations) currently have a large incentive to 'freeload', keeping their own emissions high while hoping that other nations will reduce theirs. Strategies to combat freeloading in this game will involve incentives for players to reduce their emissions, and/or sanctions for freeloading (**Tavoni et al., 2011; MacKay et al., 2015; Schmidt & Ockenfels, 2021**). However, on a global scale, such measures cannot be forced on all nations by an outside party; therefore, this kind of approach relies on communication and co-operation between nations. An important goal is the 'self-enforcing' strategy, in which no player has an incentive to deviate from the optimal strategy (**Barrett, 1994; Dutta & Radner, 2004; Heitzig, Lessmann & Zou, 2011**). This can be enforced if players form coalitions where each member must meet an agreed carbon emission reduction target, with some punishment for failing to do so; however, nations are strongly disincentivised from joining such coalitions if they believe they may earn punishments. A possible solution was discussed by Heitzig et. al., (**2011**), which they termed 'linear compensation'; punishments earned by the members are related to how well other members are also performing. So, if all nations in the coalition find it difficult to reduce emissions, all punishments will be lowered. This considerably alleviates the uncertainty involved in predicting how much a nation will be able to reduce emissions.

Of course, in practice it will still be difficult to persuade national governments to sign up to such coalitions if the only possible outcome is that they can be punished for failing to meet environmental targets. For a collaborative approach to be politically palatable, there needs to be some possibility of reward for meeting the target, as well as sanctions for failing. An example of this type of approach is in carbon trading, which is a system that aims to reduce CO2 emissions. Carbon markets allow trading of carbon credits and carbon offsets (**Newell, Pizer & Raimi, 2014; Shen, Zhao & Deng, 2020; Chai et al., 2022**).

Carbon credits and carbon offsets work via two different mechanisms:

Carbon credits- Government regulators set a limit on CO_2 emissions, and issue carbon credits to companies. Each carbon credit allows the company to emit a unit of CO_2 into the atmosphere. If a company is likely to exceed the emissions that it is allowed, it must either purchase extra carbon credits (from other companies that have not reached their maximum allowed level of emissions) or be fined. This mechanism provides an incentive for organisations to reduce their level of CO_2 emissions, since they can be fined if they do not comply but can be rewarded (by selling their extra carbon credits) if they manage to reduce their emissions below their cap.

Carbon offsets involve activities that are considered to remove CO_2 from the atmosphere, such as planting forests or developing renewable energy capacity to replace fossil fuels. Organisations that carry out such activities issue carbon offsets, which are then purchased by CO_2 emitting companies and used to 'offset' their CO_2 production.

The main difference between these two mechanisms is that carbon offsets are largely a 'voluntary' trade in carbon while carbon credits are non-voluntary and subject to the government or regulatory body setting the carbon reduction targets.

Allowing the carbon markets to regulate and, over time, improve CO2 emissions is an appealing idea and has the benefit that it provides incentives for 'good behaviour' on the part of governments and organisations, rather than simple punishments for exceeding CO2 emissions targets. However, there may be unintended consequences of using carbon trading in this way. There is, indeed, a risk that organisations will make exaggerated claims of their 'environmental friendliness' based on carbon offsetting and this will allow complacency on the part of governments who should be pursuing every possible avenue to increase sustainability in this area (**Trouwloon et al., 2023**). Furthermore, there is a risk that the use of carbon offsetting can create ethical injustices, such as the creation of polluted 'hotspots' where organisations have simply continued to pollute their local areas while paying for carbon credits so as to avoid repercussions (**Lejano, Kan & Chau, 2020**). However, the use of carbon trading is one of the more sophisticated instruments we currently have for encouraging businesses and governments to adopt 'sustainable' practices in terms of carbon emissions.

Scientific Approaches to Sustainability

Economic and political strategies are therefore a viable way to encourage countries to adopt sustainable behaviours. A second, and complementary, approach is to develop new technologies that make it easier for communities to live sustainably. A clear example of this is in the field of energy generation- if we can develop better methods for generating energy from renewable sources, such that those methods become more commercially viable, then it will become easier to persuade governments and communities to adopt these methods and reduce their carbon dioxide emissions. Developing new technologies is traditionally the preserve of so-called ‘hard’ science (physics, engineering, materials science, chemistry…) and currently there are massive research efforts being undertaken in all of these fields. However, developing a new and sustainable technology is not enough in itself. For the new technology to have an impact, it also must be commercially viable and ideally it should not come with environmental disadvantages of its own.

There are numerous ways in which we could judge whether a system is ‘sustainable’. Bell and Morse have substantially reviewed the concept of ‘sustainability indicators’, which are quantitative measures of sustainability (**Bell & Morse, 2008, 2013**). Relevant indicators are highly system-specific; e.g., if studying the health of an ecosystem, one might measure the number of species present or the number of individuals of a key species; if studying climate change, one might measure total carbon emissions or average atmospheric temperature, etc. The main issue with selecting indicators in this way is that governments (or corporations, or individuals…) will have some natural motivation to select the indicators that present their results in the best possible light, thus reducing the objectivity of the measurement. Despite this, however, it is still worth attempting to quantify efforts towards sustainability, otherwise no judgement is possible and future efforts to improve sustainability cannot be optimised.

Sustainability indicators do have limitations. A single sustainability indicator may give some idea of whether a particular part of a system is doing ‘well’ but may be too simple to form a judgement about the whole system. In the context of efforts to make manufacturing processes more sustainable, analysing the sustainability of a given process is likely to be rather complex, depending on the materials used for the process, energy sources used, and how waste is disposed of. The idea of ‘circularity’ is becoming prevalent here and is illustrated in figure 2; in a ‘circular’ economy, once a product reaches its end-of-life it is either re-used or else the raw materials are extracted from it and recycled, such that resources are not discarded as waste but recirculated indefinitely (**Blomsma & Brennan, 2017; Korhonen, Honkasalo & Seppälä, 2018; Arruda et al., 2021**). Many of our current manufacturing processes are far from this ideal, but it is increasingly becoming recognised that circularity is a worthwhile and even necessary goal. A circular economy can provide financial gains as well as environmental ones; there is a significant cost involved in extracting raw materials from their natural state, and having paid that cost it makes economic sense to keep the raw material in use for as long as possible. This idea is becoming more prevalent in decision-making by governments and businesses.

Figure 2: Diagram to illustrate the difference between (top) a traditional, 'linear' economy, in which raw materials are extracted from the environment, used in manufacturing, and then disposed of; and (bottom) a 'circular' economy, in which materials are kept in use for as long as possible by reusing or recycling products at their end-of-life.

Having acknowledged that circular processes are preferable to linear ones (in which raw materials are extracted, used, and discarded), we need to develop tools in order to analyse the 'circularity' of a particular manufacturing process. Modern manufacturing processes are often highly complex, involving many components or materials obtained from multiple different sources. In order to quantify the overall environmental impact of a particular manufactured product, we increasingly turn to a set of data analysis tools termed 'Life Cycle Analysis' (LCA) (**Ayres, 1995**). As the name suggests, this involves an attempt to quantify the materials and energy used at all stages of the product's life (manufacturing, distribution, use, disposal at end-of-life). The history of this type of approach has been summarised by Guinée et. al., (**2011**) who noted that LCAs have become more complex over time and have been applied to a wider range of potential products and processes (including in some areas that are non-manufacturing, such as tourism). LCA is not an infallible, objective tool; it relies on the analyst to make a thorough inventory of material and energy flows, and to quantify these. We can ask legitimate questions about the objectivity of the human analyst making this inventory- if we were to ask X different analysts to perform LCA on a particular product, would they produce x different results? To what extent can LCA be standardised? International standards for LCA have been introduced (**Finkbeiner et al., 2006; Heijungs, Huppes & Guinée, 2010; Klöpffer, 2012**), which go some way to addressing this issue, but do not completely nullify it. There is always a risk that the outcome of a particular LCA is affected by biases on the part of the analyst, in terms of which material and energy flows they consider most important and how these are measured. However, this does not make LCA useless; it should be regarded as an imperfect, but useful, tool for making value judgements about products and processes.

Put like this, LCA sounds like a rather abstract concept, so let us consider it in the context of a problem that is currently of considerable interest in the 'real world'- electric cars. There is increasing public awareness that electric cars are potentially better for the environment than 'conventional' cars powered by petrol or diesel. Electric cars are better for the environment because driving an electric car causes a lower level of carbon dioxide emission into the atmosphere than does the conventional car (over the course of the whole life cycle of the car- manufacturing, use and disposal). However, there can be confusion about *why* electric cars are an improvement. After all, their batteries must be charged from somewhere, and if that somewhere is the national grid, then some fossil fuel must be used to generate electricity to charge the battery (with corresponding CO_2 emissions). Furthermore, electric car batteries themselves seem like rather environmentally 'unfriendly' objects- they are complex items that require rare metals and toxic chemicals in their manufacture, and they are difficult to dispose of/recycle at their end-of-life. However, against this, we should consider that electric cars are on average more efficient than conventional ones, so less fuel is required at the electric power generator to charge the car battery than would be used by a conventional combustion engine inside a car (over the course of the car's life). Furthermore, the national grid draws on energy from renewable sources and nuclear power, as well as from fossil fuels; charging batteries from these sources also reduces the associated amount of carbon dioxide released into the atmosphere over the car's lifetime. So, how can we judge whether an electric car is indeed a 'greener' option than a conventional one? Clearly, this is a question that LCA analysis can help to clarify, and the number of these analyses available in the literature is increasing rapidly. For the reasons outlined above, the value of LCA will be increased if analyses from several sources are compared in order to draw meaningful conclusions. A recent review by Temporelli et. al., (**2020**) compared 17 LCAs on the subject of electric vehicles. These authors evaluated the LCAs against a series of criteria (does the LCA consider all parts of the battery, does it consider all stages of the battery's lifetime 'from cradle to grave', *etc*) and concluded that while there was a great deal of variability across the studies, overall electric cars had a lower impact on the environment than conventional ones.

Estimates of environmental impact are rarely simple, which is why so much variation occurs in the numerical values that will be produced as part of a single LCA. In the case of carbon dioxide emissions, the relevant values even depend on the country where a car is being used. In a report by Hall and Lutsey (**2018**) an electric car running in the UK (where the national grid runs on approx. 30% renewable energy sources) was estimated to produce 125 g of carbon dioxide per km driven by the car over the course of its lifetime. For contrast, a similar car driven in Norway (where a large percentage of electric energy is generated by hydropower) was estimated to produce approx. 75 g/km, while an average 'conventional' (petrol/diesel powered) car produced >250 g/km. The question of how to increase the proportion of the UK's energy produced from 'low carbon' sources (i.e., renewables and nuclear) is in itself very demanding, and will be a matter for policymakers as much as for engineers (**MacKay, 2008**). However, decarbonising the UK's energy supply is not the only way to reduce the environmental impact of electric cars. Ideally, we would also like to improve the efficiency and performance of car batteries, and to increase the amount of car batteries that are recycled, making the car manufacturing process more circular.

Most modern electric cars use batteries that are based on lithium-ion chemistry (**Goodenough, 2018; Kim et al., 2019a**). These batteries have a number of advantages, including high energy density and the ability to be charged and discharged over many cycles with minimal loss of performance. Further improvements in battery performance and battery life can come either from improved engineering (making use of the power provided by the battery) or from changes to the chemistry of the materials used in the batteries. Batteries are electrochemical storage systems and so any step changes in improved battery performance are likely to come from changes in the chemistry of the system, and there are a large number of possible research directions in this area (**Kim et al., 2019b; Grey & Hall, 2020**)

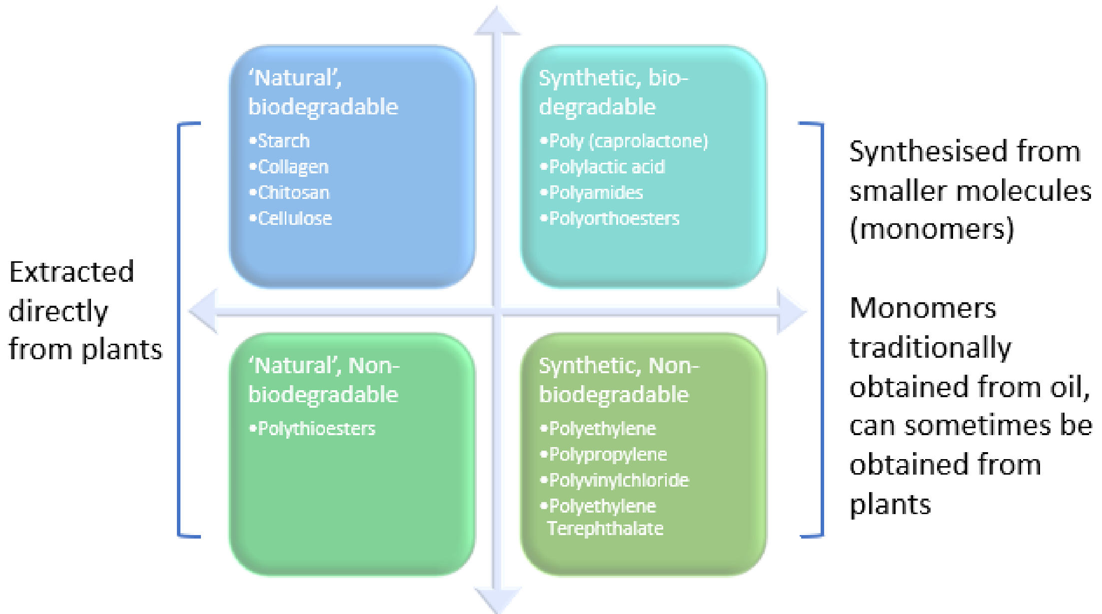
Meanwhile, the chemistry that makes batteries effective power sources also poses problems in terms of their environmental impact. The operation of lithium-ion batteries relies on metals that are in finite supply on Earth (this includes lithium, but also the cathode of the battery incorporates other metals such as cobalt, nickel, and manganese) and are extracted by mining, which in itself consumes a large amount of energy. If car batteries could be effectively recycled, then the energy cost of manufacturing the batteries could be reduced, along with the drain on the planet's resources; furthermore, an effective recycling strategy is needed to prevent end-of-life batteries having to be sent to landfill (which will become ever less desirable as the number of electric cars in use increases). Since the expensive part of a lithium-ion battery is the metal(s) incorporated into the cathode, initial methods for dealing with spent lithium-ion batteries focused on extracting those metals. However, for a truly circular system, it would be optimal if the batteries could be taken apart and the components separated so that the whole battery can be re-used, and there is increasing awareness of this (**Huang et al., 2018; Harper et al., 2019; Marshall et al., 2020**). It remains to be seen whether that process can be made economic and scaled up for industrial use.

Car batteries are a particularly interesting example of a manufactured component that is difficult to recycle, because they are complex objects containing chemicals that may be hazardous, and the treatment of each component requires specialist knowledge and facilities. However, humanity is not coping particularly well even in recycling much simpler objects, and the ideal of a truly 'circular economy' currently seems some way off. For example, one estimate indicated that in 2015, 60-99 million metric tonnes of plastic waste were dumped into the environment globally (**Lebreton & Andrady, 2019**). Plastics are particularly useful materials due to their durability and the fact that they can be so easily moulded during the manufacturing process; however, their very durability makes plastic waste into an environmental disaster because once discarded, plastics will not degrade on a useful timescale. Plastic objects discarded into the world's oceans may remain there for centuries (**Wayman & Niemann, 2021**) with very deleterious effects on marine life and the health of the world's oceans.

As with other global environmental problems, this challenge requires more than one solution. One obvious approach is to try to stop using so much plastic in the first place; could we use other materials instead? This sounds logical- but as ever, things are not so simple. There are good reasons why plastic may be used as the material of first choice in some applications. In food packaging for example, if all current plastic bottles were replaced by glass bottles, their 'recyclability' could improve, but they would (cumulatively) be much heavier and would require more energy to transport (and therefore result in higher carbon dioxide emissions from the vehicles currently being used to transport them). Lightweighting is a significant environmental benefit of plastic, as is the reduction of food waste by the increased shelf life that is a result of wrapping food in plastic. These benefits do not negate the harmful effects that plastic can have on the environment, by being manufactured from fossil fuels and by causing waste material to remain in the environment long after it has been used and discarded. LCA can be a useful tool to examine whether the use of plastic in a particular application is worse than the use of an alternative material (**Vann, 2020; Deeney et al., 2022**). The analysis does not always disfavour the use of plastics in an application, especially if the plastic can be made re-useable instead of single-use (**Moretti et al., 2021; Deeney et al., 2022**). However, the LCA approach has its critics here, who argue that the negative effects of plastic waste are too often downplayed in LCAs (**Kousemaker, Jonker & Vakis, 2021**).

Given that plastics do have very useful properties, but are major contributors to an environmental disaster, attempting to make plastics themselves less harmful is a reasonable approach. There is a significant current research effort into the synthesis of 'bioplastics' and 'biodegradable plastics'. These are not necessarily the same thing; a bioplastic is one that is manufactured from renewable feedstocks (i.e., from plant matter such as corn, rather than from fossil fuels such as oil) whereas a biodegradable plastic is one that will degrade in the environment over a short timescale after it is disposed of. To complicate the issue further, bioplastics may be obtained by direct extraction from plants, or may be synthesised from smaller molecules that are obtained from plants. The distinction between 'natural' (directly plant-derived) and 'synthetic' (artificially made from smaller molecules) polymers is illustrated in **Error! Reference source not found.**.

Figure 3: Diagram to illustrate polymers that are directly derived from natural sources, and ones that are synthesised artificially from smaller molecules. Not all biodegradable polymers are derived directly from plants.



To derive plastics from plants rather than oil may deliver gains in sustainability, since oil is a non-renewable fossil fuel. However, we have a limited amount of land on the surface of the Earth, and a large land area is currently being used for agriculture already (often to the detriment of 'pristine' habitats such as rainforest) so that using more land to cultivate crops for plastics manufacture may not prove optimal. Careful analysis will be required to determine whether plastics derived in this manner are overall better for the environment (**Bishop, Styles & Lens, 2022**).

Biodegradable polymers also have the potential to make modern life more sustainable. A truly 'obedient' plastic could be manufactured, used for its purpose, and then simply degrade into harmless smaller molecules in the environment once disposed of. This would overcome many current problems with plastic packaging- for example, a lot of plastic packaging thrown out by households cannot be currently recycled because it is contaminated by food, but if the packaging were compostable then the food waste could be composted along with the packaging. The chemistry of biodegradable large molecules has been enthusiastically developed recently, and gains have been made; (**Filiciotto & Rothenberg, 2021**) some of these polymers have even got as far as commercial use, with a rise in the availability of 'compostable' drinks cups being sold at various venues. As is often the case, however, the solutions so far are imperfect; many commercially available 'compostable' cups are based on polylactic acid (PLA), which is technically compostable but only in an industrial facility. Throwing PLA on to an average garden compost heap would not work, because it requires specific conditions (e.g., high temperatures and pressures) to degrade. However, commercial interest in compostable packaging is high and is likely to deliver substantial improvements in this area.

Conclusion

Human civilisation is now completely unsustainable at its current level, and the scale of measures needed to make it sustainable are gargantuan. In this review it is possible to give only a flavour of the scale of the problems facing our global society. In describing some select examples, however, it is hopefully made clear that the solutions will not come from one specific sector or academic field but will require input from experts in diverse areas from economics and data analysis to engineering and materials science. Such an integrated effort is a true multidisciplinary approach. We must hope that it will be enough.

Dr Jean Marshall is a Research Fellow at WMG (University of Warwick). Her research interests include novel polymeric materials for use in secondary batteries, benign methods for polymer processing, and the circular economy. At WMG she has worked on a variety of projects including novel binder materials for battery anodes, battery recycling, and solid-state electrolytes. Before joining WMG, she worked in industry for two years on novel polymeric formulations in ink formulations; prior to this she gained postdoctoral research experience on stimulus-responsive polymeric materials. She completed her PhD in surface-initiated polymer chemistry from the University of Cambridge.

References

Arruda, E.H. *et al.* (2021) 'Circular economy: A brief literature review (2015–2020)', *Sustainable Operations and Computers*, 2, pp. 79–86. DOI: 10.1016/j.susoc.2021.05.001 [Accessed: 14 July 2023].

Ayres, R.U. (1995) 'Life cycle analysis: A critique', *Resources, Conservation and Recycling*, 14(3–4), pp. 199–223. DOI: 10.1016/0921-3449(95)00017-D [Accessed: 14 July 2023].

Barrett, S. (1994) 'Self-enforcing international environmental agreements', *Oxford Economic Papers*, 46, pp. 878–894. DOI: 10.1093/oep/46.Supplement_1.878 [Accessed: 14 July 2023].

Bell, S. and Morse, S. (2008) *Sustainability Indicators: Measuring the Immeasurable?* 2nd edn. Routledge.

Bell, S. and Morse, S. (2013) *Measuring sustainability: Learning by doing*, *Measuring Sustainability: Learning by Doing*. Taylor and Francis. DOI: 10.4324/9781849771962 [Accessed: 14 July 2023].

Bishop, G., Styles, D. and Lens, P.N.L. (2022) 'Land-use change and valorisation of feedstock side-streams determine the climate mitigation potential of bioplastics', *Resources, Conservation and Recycling*, 180, p. 106185. DOI: 10.1016/j.resconrec.2022.106185 [Accessed: 14 July 2023].

Blomsma, F. and Brennan, G. (2017) 'The Emergence of Circular Economy: A New Framing Around Prolonging Resource Productivity', *Journal of Industrial Ecology*, 21(3), pp. 603–614. DOI: 10.1111/jiec.12603 [Accessed: 14 July 2023].

Catton, W.R. (1982) *Overshoot: The Ecological Basis of Revolutionary Change*. University of Illinois Press.

Chai, S. *et al.* (2022) 'Is Emissions Trading Scheme (ETS) an Effective Market-Incentivized Environmental Regulation Policy? Evidence from China's Eight ETS Pilots', *International Journal of Environmental Research and Public Health*, 19(6). DOI: 10.3390/ijerph19063177 [Accessed: 14 July 2023].

Deeney, M. *et al.* (2022) 'Human health effects of recycling and reusing plastic packaging in the food system: a systematic review and meta-analysis of life cycle assessments', *medRxiv*, p. 2022.04.22.22274074. DOI: 10.1101/2022.04.22.22274074 [Accessed: 14 July 2023].

Dutta, P.K. and Radner, R. (2004) 'Self-enforcing climate-change treaties', *Proceedings of the National Academy of Sciences of the United States of America*, 101(14), pp. 5174–5179. DOI: 10.1073/pnas.0400489101 [Accessed: 14 July 2023].

Fanning, A.L. *et al.* (2022) 'The social shortfall and ecological overshoot of nations', *Nature Sustainability*, 5(1), pp. 26–36. DOI: 10.1038/s41893-021-00799-z [Accessed: 14 July 2023].

Filiciotto, L. and Rothenberg, G. (2021) 'Biodegradable Plastics: Standards, Policies, and Impacts', *ChemSusChem*, 14(1), pp. 56–72. DOI: 10.1002/cssc.202002044 [Accessed: 14 July 2023].

Finkbeiner, M. *et al.* (2006) 'The new international standards for life cycle assessment: ISO 14040 and ISO 14044', *International Journal of Life Cycle Assessment*, 11(2), pp. 80–85. DOI: 10.1065/lca2006.02.002 [Accessed: 14 July 2023].

Global Footprint Network (2022) *Past Earth Overshoot Days*. Available at: https://www.overshootday.org/newsroom/past-earth-overshoot-days/ [Accessed: 15 August 2022].

Goodenough, J.B. (2018) 'How we made the Li-ion rechargeable battery: Progress in portable and ubiquitous electronics would not be possible without rechargeable batteries. John B. Goodenough recounts the history of the lithium-ion rechargeable battery', *Nature Electronics*, 1(3), p. 204. DOI: 10.1038/s41928-018-0048-6 [Accessed: 14 July 2023].

Grey, C.P. and Hall, D.S. (2020) 'Prospects for lithium-ion batteries and beyond—a 2030 vision', *Nature Communications*, 11(1), pp. 1–4. DOI: 10.1038/s41467-020-19991-4 [Accessed: 14 July 2023].

Guinée, J.B. *et al.* (2011) 'Life cycle assessment: Past, present, and future', *Environmental Science and Technology*, 45(1), pp. 90–96. DOI: 10.1021/es101316v [Accessed: 14 July 2023].

Hall, D. and Lutsey, N. (2018) *Effects of battery manufacturing on electric vehicle life-cycle greenhouse gas emissions - International Council on Clean Transportation*.

Harper, G. *et al.* (2019) 'Recycling lithium-ion batteries from electric vehicles', *Nature*. Nature Publishing Group, pp. 75–86. DOI: 10.1038/s41586-019-1682-5 [Accessed: 14 July 2023].

Heijungs, R., Huppes, G. and Guinée, J.B. (2010) 'Life cycle assessment and sustainability analysis of products, materials and technologies. Toward a scientific framework for sustainability life cycle analysis', *Polymer Degradation and Stability*, 95(3), pp. 422–428. DOI: 10.1016/j.polymdegradstab.2009.11.010 [Accessed: 14 July 2023].

Heitzig, J., Lessmann, K. and Zou, Y. (2011) 'Self-enforcing strategies to deter free-riding in the climate change mitigation game and other repeated public good games', *Proceedings of the National Academy of Sciences of the United States of America*, 108(38), pp. 15739–15744. DOI: 10.1073/pnas.1106265108 [Accessed: 14 July 2023].

Huang, B. *et al.* (2018) 'Recycling of lithium-ion batteries: Recent advances and perspectives', *Journal of Power Sources*. Elsevier B.V., pp. 274–286. DOI: 10.1016/j.jpowsour.2018.07.116 [Accessed: 14 July 2023].

Kim, T. *et al.* (2019a) 'Lithium-ion batteries: outlook on present, future, and hybridized technologies', *Journal of Materials Chemistry A*, 7(7), pp. 2942–2964. DOI: 10.1039/C8TA10513H [Accessed: 14 July 2023].

Kim, T. *et al.* (2019b) 'Lithium-ion batteries: outlook on present, future, and hybridized technologies', *Journal of Materials Chemistry A*, 7(7), pp. 2942–2964. DOI: 10.1039/C8TA10513H [Accessed: 14 July 2023].

Klöpffer, W. (2012) 'The critical review of life cycle assessment studies according to ISO 14040 and 14044', *International Journal of Life Cycle Assessment*. Springer, pp. 1087–1093. DOI: 10.1007/s11367-012-0426-7 [Accessed: 14 July 2023].

Korhonen, J., Honkasalo, A. and Seppälä, J. (2018) 'Circular Economy: The Concept and its Limitations', *Ecological Economics*, 143. DOI: 10.1016/j.ecolecon.2017.06.041 [Accessed: 14 July 2023].

Kousemaker, T.M., Jonker, G.H. and Vakis, A.I. (2021) 'LCA Practices of Plastics and Their Recycling: A Critical Review', *Applied Sciences*, 11(8), p. 3305. DOI: 10.3390/app11083305 [Accessed: 14 July 2023].

Kuhlman, T. and Farrington, J. (2010) 'What is Sustainability?', *Sustainability*, 2(11), pp. 3436–3448. DOI: 10.3390/su2113436 [Accessed: 14 July 2023].

Lebreton, L. and Andrady, A. (2019) 'Future scenarios of global plastic waste generation and disposal', *Palgrave Communications*, 5(1), pp. 1–11. DOI: 10.1057/s41599-018-0212-7 [Accessed: 14 July 2023].

Lejano, R.P., Kan, W.S. and Chau, C.C. (2020) 'The Hidden Disequities of Carbon Trading: Carbon Emissions, Air Toxics, and Environmental Justice', *Frontiers in Environmental Science*, 8, p. 593014.

MacKay, D. (2008) *Sustainable Energy- without the hot air*. Cambridge: UIT.

MacKay, D.J.C. *et al.* (2015) 'Price carbon - I will if you will', *Nature*, 526(7573), pp. 315–316. DOI: https://doi.org/10.1038/526315a [Accessed: 14 July 2023].

Marshall, J. *et al.* (2020) 'Disassembly of Li Ion Cells- Characterization and Safety Considerations of a Recycling Scheme', *Metals*, 10(6), p. 773. DOI: 10.3390/met10060773 [Accessed: 14 July 2023].

Mensah, J. (2019) 'Sustainable development: Meaning, history, principles, pillars, and implications for human action: Literature review', *Cogent Social Sciences*. Edited by S. Ricart Casadevall, 5(1), p. 1653531. DOI: 10.1080/23311886.2019.1653531 [Accessed: 14 July 2023].

Moretti, C. *et al.* (2021) 'Cradle-to-grave life cycle assessment of single-use cups made from PLA, PP and PET', *Resources, Conservation and Recycling*, 169, p. 105508. DOI: 10.1016/j.resconrec.2021.105508 [Accessed: 14 July 2023].

Newell, R.G., Pizer, W.A. and Raimi, D. (2014) 'Carbon Markets: Past, Present, and Future', *Annual Review of Resource Economics*, 6, pp. 191–215.

Ruggerio, C.A. (2021) 'Sustainability and sustainable development: A review of principles and definitions', *Science of the Total Environment*, 786, p. 147481. DOI: 10.1016/j.scitotenv.2021.147481 [Accessed: 14 July 2023].

Sadigov, R. (2022) 'Rapid Growth of the World Population and Its Socioeconomic Results', *Scientific World Journal*, 2022. DOI: 10.1155/2022/8110229 [Accessed: 14 July 2023].

Sakalasooriya, N. (2021) 'Conceptual Analysis of Sustainability and Sustainable Development', *Open Journal of Social Sciences*, 09(03), pp. 396–414. DOI: 10.4236/jss.2021.93026 .

Schmidt, K.M. and Ockenfels, A. (2021) 'Focusing climate negotiations on a uniform common commitment can promote cooperation', *Proceedings of the National Academy of Sciences of the United States of America*, 118(11), p. e2013070118. DOI: 10.1073/pnas.2013070118 [Accessed: 14 July 2023].

Shen, N., Zhao, Y. and Deng, R. (2020) 'A review of carbon trading based on an evolutionary perspective', *International Journal of Climate Change Strategies and Management*. Emerald Group Holdings Ltd., pp. 739–756. DOI: 10.1108/IJCCSM-11-2019-0066 [Accessed: 14 July 2023].

Tavoni, A. *et al.* (2011) 'Inequality, communication, and the avoidance of disastrous climate change in a public goods game', *Proceedings of the National Academy of Sciences of the United States of America*, 108(29), pp. 11825–11829. DOI: https://doi.org/10.1073/pnas.1102493108 [Accessed: 14 July 2023].

Temporelli, A., Carvalho, M.L. and Girardi, P. (2020) 'Life Cycle Assessment of Electric Vehicle Batteries: An Overview of Recent Literature', *Energies*, 13(11), p. 2864. DOI: 10.3390/en13112864 [Accessed: 14 July 2023].

Trouwloon, Danick. *et al.* (2023) 'Understanding the Use of Carbon Credits by Companies: A Review of the Defining Elements of Corporate Climate Claims', *Global Challenges*, 7(4), p. 2200158.

Vann, K. (2020) *Are life-cycle assessments worth the (recycled) paper they're printed on?* Available at: https://ensia.com/features/life-cycle-assessment/ [Accessed: 12 September 2022].

Wackernagel, M. *et al.* (2002) 'Tracking the ecological overshoot of the human economy', *Proceedings of the National Academy of Sciences of the United States of America*, 99(14), pp. 9266–9271. DOI: 10.1073/pnas.142033699 [Accessed: 14 July 2023].

Wayman, C. and Niemann, H. (2021) 'The fate of plastic in the ocean environment-a minireview', *Environmental Science: Processes and Impacts*, 23(2), pp. 198–212. DOI: 10.1039/d0em00446d [Accessed: 14 July 2023].

Wood, P.J. (2012) 'Climate Change and Game Theory: A Mathematical Survey', *SSRN Electronic Journal* [Preprint]. DOI: 10.2139/ssrn.1883944 [Accessed: 14 July 2023].

'World Commission on Environment and Development' (1987) *Our Common Future.* Oxford.

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