UNIVERSITY *of York*

This is a repository copy of *Circular economy design considerations for research and process development in the chemical sciences*.

White Rose Research Online URL for this paper:
https://eprints.whiterose.ac.uk/103041/

Version: Accepted Version

Article:

Clark, James Hanley orcid.org/0000-0002-5860-2480, Farmer, Thomas James orcid.org/0000-0002-1039-7684, Herrero-Davila, Lorenzo et al. (1 more author) (2016) Circular economy design considerations for research and process development in the chemical sciences. Green Chemistry. pp. 3914-3934. ISSN 1463-9262

https://doi.org/10.1039/C6GC00501B

Reuse

Items deposited in White Rose Research Online are protected by copyright, with all rights reserved unless indicated otherwise. They may be downloaded and/or printed for private study, or other acts as permitted by national copyright laws. The publisher or other rights holders may allow further reproduction and re-use of the full text version. This is indicated by the licence information on the White Rose Research Online record for the item.

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

White Rose
university consortium
Universities of Leeds, Sheffield & York

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

Circular economy design considerations for research and process development in the chemical sciences

James H. Clark*, Thomas J. Farmer, Lorenzo Herrero-Davila, and James Sherwood

Green Chemistry Centre of Excellence, Department of Chemistry, University of York, UK, YO10 5DD.
E-mail: james.clark@york.ac.uk

Abstract

A circular economy will look to chemistry to provide the basis of innovative products, made from renewable feedstocks and designed to be reused, recycled, or the feedstock renewed through natural processes. The substances that products are made of will increasing be treated as a resource equal to the raw materials, and not just disposed of. This perspective discusses the role of chemists in a world without waste.

Graphical abstract

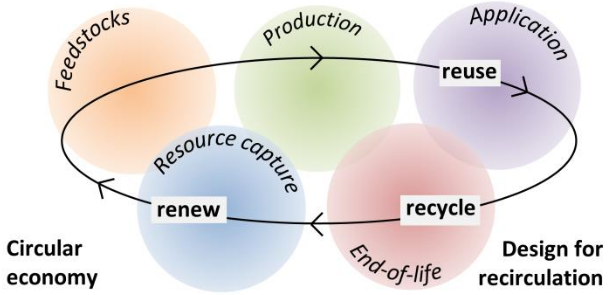


Table of contents entry

This perspective on the circular economy is a call for chemists to value resources through responsible product design.

1. Introduction to the circular economy

On the 2nd December 2015 the European Commission (EC) released an “ambitious” proposal for a circular economy.[1-3] Accordingly now would seem an opportune time to interpret the announcement, consider the opinions expressed thus far on the topic, and evaluate what will be expected from chemists working in research and development and the responsibility of chemical manufacturers in a circular economy.

Reacting to major recessions in the first part of the 20th century, the global economic model was designed to rely heavily on ‘planned obsolescence’ in order to grow the economy and sustain the job market.[4] However this approach is only achieved at the expense of resources and therefore cannot be continued indefinitely. As well as encouraging shorter product lifespans, to a certain extent a conventional linear economy also rewards product inefficiency, overconsumption, and therefore wastefulness.[5] With the increase in consumption created by a growing world population and greater affluence amongst developing nations,[6] the problems of a linear, resource-to-waste economy are becoming more acute.

Following the most recent global recession of 2009, solutions for a more stable economic model have looked to embrace interlinked problems such as depleting fossil reserves while also addressing the pollution they cause.[7] A circular economy increases the value of a material resource by maximising its conversion into products (high value), and in doing so eliminating waste (low value). In addition, the lifetime of products is increased through responsible product design.[8] When a product reaches the end of its function, reuse and recycling provides an opportunity to prolong the usefulness of its constituent parts even further. Meanwhile the inherent value of the material embodied in the product is extended rather than wasted. Demand for finite resources is therefore lessened, and consequently a circular economy is a means to reduce greenhouse gas emissions.

Whereas the original (and since withdrawn) European circular economy legislative proposal was focused on waste management, this was replaced with a more comprehensive vision of a closed loop value chain from the outset of the latest proposal when first planned in early 2015 (Figure 1).[9] Upon completion of the European Commission’s plans for a circular economy, it can be expected that manufacturers will need to demonstrate that their products have been designed in such a way that their potential for reuse and recycling is maximised. If chemists can appreciate the demands imposed on product designers and manufacturers by a circular economy, it becomes a stimulating driver for research and innovation, rather than a burden.

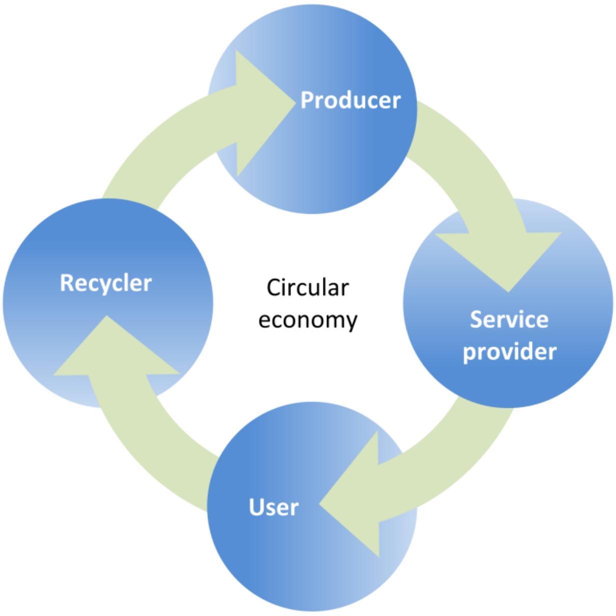


Figure 1. A simplified view of a circular economy in terms of material flow embodied as functional products.

In order to reduce waste and material consumption, a circular economy will require consumers and procurers to increase their association of value with the desirable function a given product provides, not the product itself. This is a considerable philosophical adjustment that will take time to become widely accepted.[10] Short product lifespans encourage repeated consumption, stabilising and protracting their markets to the benefit of the suppliers.[11] An alternative to a business model based on product sales is one of service provision.[12] When being paid for a particular service rather than to provide a certain quantity of product, the excessive consumption of primary resources and the production of replacement products actually becomes a hindrance to manufacturers.[13] In a service-based business model there is a clear economic incentive to reduce material use and increase product efficiency and longevity. The elimination of waste through innovative product design for enhanced reuse or recycling opportunities fits this philosophy perfectly. It is therefore to be expected that both suppliers and consumers will be seeking new materials and formulations, and the responsibility and opportunity will be with the scientific community to initiate relevant projects and develop the appropriate substances.

It is not just consumer end products that are being rethought using a mentality of service provision. The concept of ‘chemical leasing’ is being promoted by the United Nations Industrial Development Organization (UNIDO).[14,15] The origin of this waste minimising business approach can be traced to well established chemical management strategies where using less chemicals has been equated to reduced cost, risk and exposure.[16] In this business model it is the service provided by that chemical that is paid for, (*e.g.* volume of water treated, number of articles painted) and not the quantity of chemicals purchased. With efficiency rewarding the supplier instead of material consumption, waste reduction is achieved. UNIDO claims that, by decoupling payment from consumption, chemical leasing encourages better management of chemicals with beneficial consequences for the environment (Table 1).[17] Similar types of scheme are now operating in the consumer sector, from computers to clothes, and are particularly beneficial to less durable products if refurbishment or remanufacturing is straightforward.[18] Extended producer responsibility can incentivise the inclusion of environmental aspects into the design of products, but how best to implement this without unnecessarily penalising businesses or misplacing accountability is still actively discussed in the literature.[19]

Table 1. Specific examples of chemical leasing projects.[15]

Process	Country	Payment	Benefits
Metal cleaning	Austria	*per number of parts cleaned*	Volume of solvent reduced by 71%, energy consumption halved.
Waste water treatment	Columbia	*per cubic metre of water*	Chemical consumption halved.
Dyeing	India	*per kilogram of textiles*	Annual savings: 2 million kWh of energy, 78 tonnes of dyes, 75 million litres of water.
Painting	Sri Lanka	*per area of building painted*	Material use 10% more efficient. Reductions in water use and packaging also achieved.
Machine lubrication	Serbia	*per hour of operation*	Hazardous chemicals replaced, and 6.5 million litres of water saved.

Products designed to facilitate their own reuse and recycling allows the service they provide to be continued repeatedly, without unnecessarily depleting natural resources. When the design of a product makes recycling or disassembly for refurbishment and reuse technically impossible, it is equivalent to a reduction in the service that can be provided by the material resource contained in that product. Certain combinations of different materials can make separation slow or otherwise difficult, as can the means by which the components are joined.[20] Collection and treatment of products at the end of their functioning life is equally important. If the components of the waste stream are not easily separated, or they consist of chemicals and materials without an established means of being recycled, the valuable resource contained in each waste product will not be retained within the circular economy.

The circular economy is clearly the combination of many initiatives.[21] The complete outlook of resource efficiency as a waste prevention strategy has been speculated as capable of annually saving 30 million tonnes of primary manufacturing feedstock in the UK alone by 2020. Waste would be reduced by 20%.[22] The resulting economic benefit across European manufacturing sectors is potentially hundreds of billions of Euros every year.[23] A circular economy is certainly not limited to Europe, with other countries including China,[24] and the USA,[25] possessing their own initiatives. China in particular has an advanced circular economy policy framework, first implemented in 2002, which has evolved from basic recycling laws into a comprehensive ideology based on industrial symbiosis and resource conservation.[24]

2. Chemical and material design for zero waste

The role of chemistry in our society is not to just to continue creating the established plastic products, additives for formulations, and other functional chemicals. Chemists and chemical engineers should share responsibility for environmentally sound product design with manufacturers, by developing appropriate chemical substances and processes for a circular economy.[26] As well as designing substances to meet specific application criteria, *e.g.* durable, non-toxic, porous *etc*., additional 'end-of-life' considerations need to be balanced against product performance. The ever demanding needs of modern society are protected by constantly revised chemical legislation.[27] Increasingly this will be steered by a need to preserve finite resources. Requirements down to the level of individual chemical substances for the downstream reuse and recyclability of consumer products must be at the forefront of future scientific developments. For example, immobilisation of a catalyst allows it to be reused. This approach can retain the high activity typical of homogeneous catalysts and maybe even offer improved reaction selectivity.[28] This is an especially useful approach for creating reusable asymmetric catalysts, and easily manufactured asymmetric heterogeneous catalysts continue to be discovered.[29] Similarly, introducing susceptible chemical bonds into surfactants to make them biodegrade rapidly in the environment (organic recycling) can be achieved without impairing product performance.[30]

A recent article by Constable (presently head of the ACS Green Chemistry Institute) establishes a parallel between product design in its conventional sense and green chemistry practices.[31] The motivation to substitute toxic reagents and develop less wasteful reactions (equated by Constable to a 'design ethic') is still the preserve of chemists and chemical engineers with the desire and imagination to change the *status quo*. Whereas green chemistry can be interpreted as a guiding philosophy for improving chemical products and process development,[32] ultimately it is legislation (and sometimes customer pressure) that will force change. This is beginning to be seen with the European REACH regulation (registration, evaluation, authorisation and restriction of chemicals) which is leading to the identification and restriction of toxic or environmentally hazardous substances.[33] Now measures to promote a circular economy will require European chemical producers and importers to change their habits regarding how they view product design in a similar way. This must be reflected by an enthusiasm amongst an informed generation of scientists who are able to provide the expertise required. Otherwise, tightening regulation and the high associated costs (*e.g.* of additional chemical testing) could all too easily be accepted as an expensive barrier, curtailing opportunities to instigate any reform in chemical design, production and compound selection. This does not have to be the case, for it can equally be considered as a catalyst for innovation. The necessary response to the increasing need to substitute hazardous chemicals is the development of novel but carefully considered molecules.

A reduction in hazardous chemical use is advantageous in a circular economy. For example, plastics without toxic additives can be recycled safely. Efforts to reduce chemical waste and hazards must be practiced in the major manufacturing centres of the world, which are not necessarily located where the most restrictive legislation presides. For the circular economy to flourish, the principles of eco-design and sustainable material use must be applied proactively, and not neglected in favour of 'end-of-pipe' treatments or low value waste management exercises. Restricting oneself to operating within the regulated controls imposed on hazardous substances will certainly curtail innovation, while investing in benign alternatives has long term benefits.

It is easy to recognise that if products are reused and recycled it lessens demand for the planet's finite resources. To actually achieve effective material recirculation in a circular economy the initial design of products is crucial. The importance of product design should not be overshadowed by waste management, which essentially has the purpose of treating waste by economical means. Waste management consists of general practices that often apply to heterogeneous and changing waste streams.[34] An understanding of the waste hierarchy established by the EU waste directive helps to visualise the relative benefits of each end-of-life option (Figure 2).[35] Products inherently designed to be quickly disassembled and either remanufactured or refurbished, or easily repaired when needed,[36] can be returned to use with high efficiency rather than risk being sent to landfill or incinerated simply out of convenience. The EC circular economy action plan proposes to revise the EU waste directive to better reflect the requirements of a circular economy.[37]

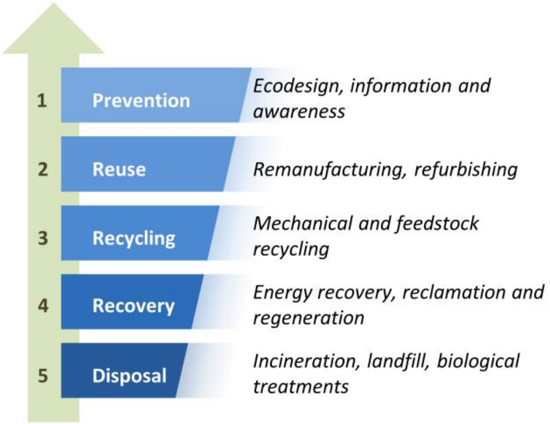


Figure 2. The waste hierarchy as defined by the European waste directive 2008/98/EC.

The design of smartphones and the habits of their users illustrate the aforementioned waste hierarchy quite well. Smartphones contain a large number of different elements (40-50 in the current generation of devices), and poor product design is well known to unnecessarily limit the feasibility of metal recycling.[38] The design of the product can also greatly impair the ability to repair any damage to the smartphone (Figure 3). If the functioning lifetime cannot be prolonged, the low recycling rate of smartphones means the material resource is frequently not adequately recirculated.[39] Repurposing smartphones is better still from a life cycle impact perspective but there is no general infrastructure in operation to conduct this policy.[40] The foreseen end-of-life option quickly falls down the waste hierarchy towards disposal because of failings in product design, waste collection, and a lack of consumer awareness.[41] This situation cannot be continued indefinitely because many of the elements that are currently used in smartphone construction will shortly exhaust their known economically viable reserves.[42,43]

Figure 3. Elemental resources and design considerations for smartphones.[36,43,44]

Dissecting the environmental impact of product design with a cradle-to-cradle perspective, the first consideration is the choice of feedstock. The expertise of those working in the chemical sciences is especially helpful here for the selection of starting materials and their optimum conversion into suitable chemical intermediates. The production of acetic acid is a simple example of this. Acetic acid is (amongst other things) a chemical intermediate and a solvent in terephthalic acid production.[45] It is also biodegradable.[46] Most acetic acid is produced from syngas.[47] Usually it is desirable to find an equivalent renewable feedstock so the existing infrastructure can continue to be used. However anaerobic digestion to give the bio-gas (methane) precursor of acetic acid, or even direct gasification of biomass to syngas, is quite wasteful when represented in terms of atom economy (Figure 4).[48] Bio-based acetic acid is conventionally made by the oxidative fermentation of carbohydrate,[45] but still the co-production of carbon dioxide means a significant part of the feedstock is wasted. Anaerobic fermentation is more attractive from a biomass utilisation perspective, and theoretically all the carbohydrate feedstock can be converted into acetic acid.[49] After use biodegradation transforms acetic acid into carbon dioxide and water, the precursors of photosynthetic biomass production. In this article the authors are limiting discussion to the material contained within products, but it should be noted that biomass production requires land, nutrients and water. Therefore the choice between suitable biomass crops should be carefully considered.[50]

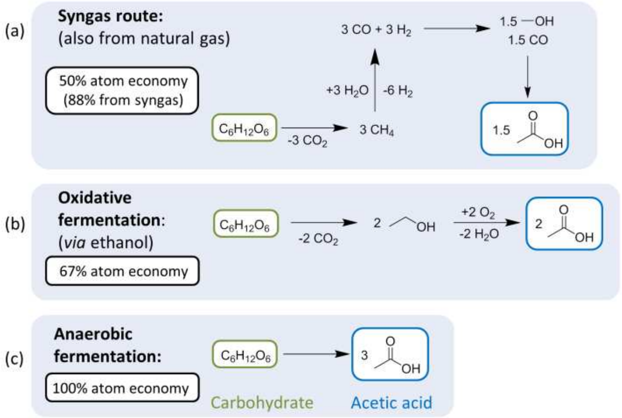


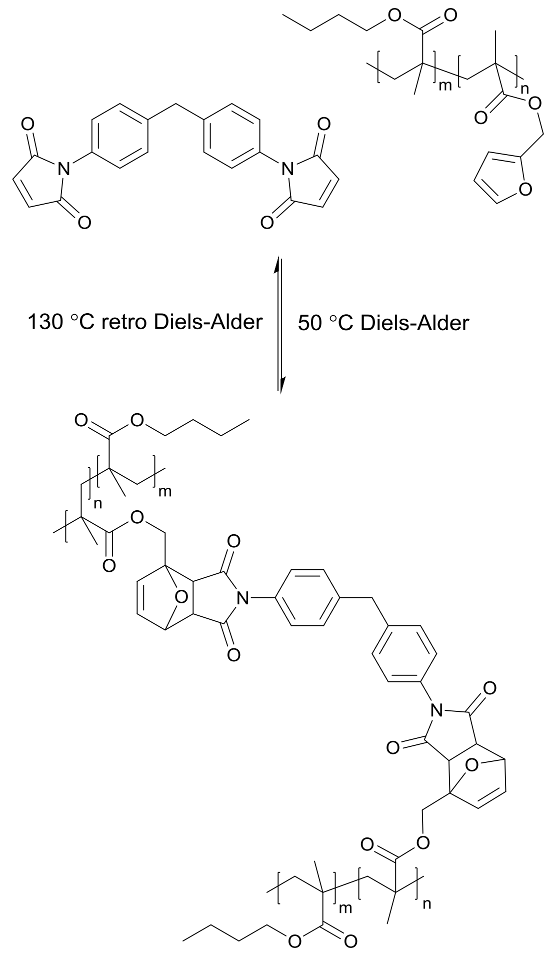
Figure 4. Idealised schematics of bio-based acetic acid production. (a) methanol carbonylation; (b) oxidation of ethanol; (c) acetogenic fermentation.

The emphasis of a circular economy on valuing resources, reducing waste and addressing climate change is clearly complemented by the ambitions of a bio-based economy.[51,52] The value of biomass as a resource for producing chemicals greatly exceeds the potential of the present day bio-fuel market.[53] As suggested for the example of acetic acid, the renewable material contained within bio-based products is recirculated through biodegradation (biological recycling) if the biomass feedstock is generated from managed forests or by sustainable crop production (including the use of processing waste streams as chemical feedstocks). However not all bio-based products are biodegradable, and the recirculation of novel bio-based products could be increased and further enhanced with the implementation of alternative end-of-life options (*e.g.* chemical recycling). The principle of the circular economy means it is not essential to immediately produce every organic product from renewable materials (biomass, CO_2, *etc.*), and so concerns over the direct and indirect consequences of land use change can be kept in check with proportional areas of land dedicated to non-food crops, including wood. To circumvent sustainable land use issues, the wastes from food crops or elsewhere in the food supply chain are ideal sources of chemicals.[54]

Wherever there is access to sustainable chemical intermediates, an efficient transformation to the end product(s) is also needed to create the best possible value. The development of low waste synthetic methodologies,[55] supplemented by the improved efficiency of catalysts made from abundant, non-toxic metals or wastes,[56] as well as biocatalysis,[57] and the careful management of other major process auxiliaries (notably solvents) is an important step towards a circular economy. The benefit of re-evaluating a synthesis, especially the number of steps and the amount and type of solvent used, has been proven on a manufacturing scale for the production of sildenafil citrate (the active pharmaceutical ingredient of Viagra™).[58] With solvent recovery organic waste was reduced from 22 liters for every kilogram of product to just 4 liters for every kilogram of product.

Not only is the synthetic route of importance, but the composition and function of the final product needs to be compatible with a circular economy. Sometimes the synthesis and function of a chemical are interconnected. The Diels-Alder reaction for example is useful for the synthesis of self-healing polymers. Waste is avoided by using a synthetic approach to polymer cross-linking that is 100% atom economic, which then also allows the polymer to repair damage to itself through the reversible Diels-Alder reaction when heated (Scheme 1).[59]

Notches in the material are repaired as the polymer crosslinks reorganise. It can be expected that with remanufacturing the polymer will have an extended lifespan as a result, and not need frequent replacement.



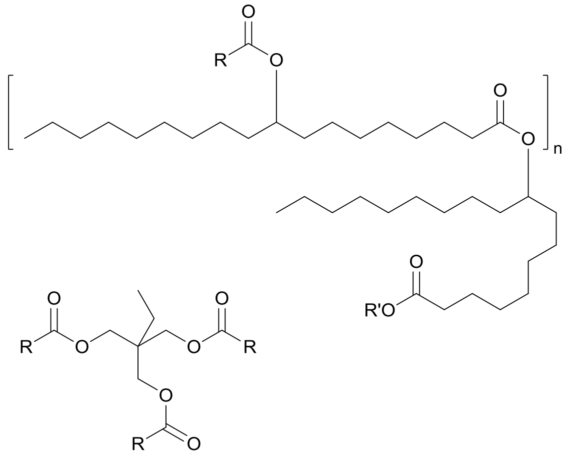
Scheme 1. A self-healing copolymer of butyl methacrylate and furfuryl methacrylate reversibly crosslinked with a bismaleimide compound.[59]

Innovation in technology and chemical design so that toxic chemicals may be replaced and unnecessary waste avoided demonstrates progress has been made, but even more will be asked of chemists in a circular economy. Beyond the development of clean synthetic methods, at the very least chemical synthesis and manufacturing must become compatible with sustainable global development goals.[60] From the legislator's perspective, products will be expected to store and retain the carbon that is a part of their chemical structure in such a way as to negate greenhouse gas (GHG) emissions.[51] In this respect the petrochemical components of a product must be constructed so that they can be disassembled and processed for complete reuse or recycling. Only those multi-component articles that can be dissembled easily can be repaired economically.[36] Alternatively the parts can be sent for remanufacturing to reduce primary feedstock use. Although retaining the value inherent to a functional end-product is ideal, when this is not possible mechanical recycling will also keep the carbon content sequestered, if on the down side the form and function of the product is lost to provide a secondary manufacturing material (Table 2). The quality of recyclates must be consistently high, and the recycling procedure efficient. This can be achieved by monitoring recycling processes and ensuring no traces of hazardous additives are present.[61] Inseparable blends of recyclable plastics with biodegradable polymers should be avoided. The quality of recycled plastics can be impaired by contaminants, or at least introduce variability in the mechanical and thermal properties of the recyclate.[62] If hazardous chemicals or biodegradable polymers are crucial to the function of an article otherwise mostly comprised of recyclable plastic, each part must be clearly identifiable and separable so that they can enter their own appropriate waste treatment streams. In order to sustain the value of chemicals and materials beyond these end-of-life processes, product design must embrace current and future practices in a manner that is consistent with the European end-of-waste framework, whereby waste is transformed into a marketable product.[35] This definition will be updated to help the European circular economy where waste is now viewed as a resource.[2,37]

Table 2. Categories of material recirculation in a circular economy.

Cycle	Level of chemical composition retained	Example
Reuse	Component parts preserved	Remanufactured parts (*e.g.* engines)
Recycle	Material/molecular (the form and function of the article is lost)	Mechanical recycling (*e.g.* PET packaging)
Renew	Elemental (molecular composition is also lost)	Biodegradation (*e.g.* compostable plastic)

There are instances where petrochemicals are not appropriate starting materials for chemical synthesis. The use of a renewable feedstock is most important when a product cannot enter a formal end-of-life waste treatment. One example is the type of lubricant used on chainsaw blades and the engines of motorboats, where essentially all the lubricant is lost to the environment.[63] In this case biodegradation of the lubricant is the preferred method of preventing pollution and long term ecotoxicity problems. Importantly for a circular economy, biodegradable products must be completely bio-based if the carbon embodied in the article is to be recirculated and not contribute to a net gain in GHG emissions (Scheme 2). Composting of bio-based products also helps balance nutrient cycles,[64] and should be considered superior to uncontrolled biodegradation in the environment but producing a lower value resource than other types of recycling. Composite materials can contain many different elements and so a carbon-centric argument does not give the complete story. The rate at which hazardous elements and compounds can enter the environment is controlled by various pieces of legislation, primarily for the benefit of human health and environmental protection. In a circular economy attempts to reclaim these materials (or ideally avoid them in the first place) must be prioritised over measures to limit the impact of hazardous substances when released into the environment.



Scheme 2. Two examples of triglyceride derived bio-lubricants. Top: an estolide ester (R' = H or 2-ethyl-1-hexyl). Bottom: a partially bio-based synthetic trimethylolpropane ester (R = fatty acid alkyl).[65]

The reuse and recycling of bio-based products is equally valid in order to avoid waste, but biodegradation of fossil derived products is not compatible with the circular economy ethos of maximising the potential of resources in a manner consistent with climate change targets.[66] Although out of the scope of this discussion, this point also highlights the need for low carbon energy to power manufacturing,[67] and products should be designed to be energy efficient in line with the EU directive on eco-design where applicable.[68] All these considerations combined provide the basis for the design, production, and end-of-life treatment of environmentally benign products (Figure 5).

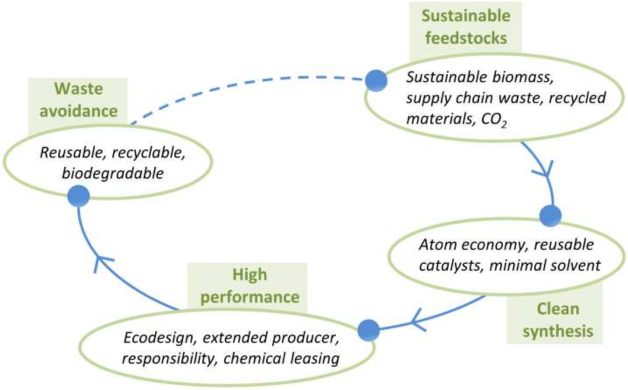
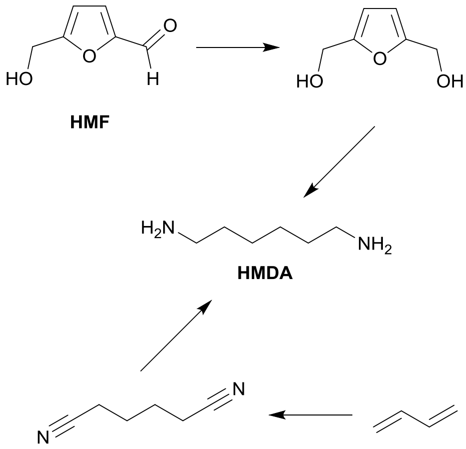


Figure 5. Cradle-to-grave life cycle considerations in product design applicable to chemical research and development.

3. Demonstrating recirculation

Contemporary use of the term 'renewable' is associated with feedstocks and energy sources, and so bio-based products would therefore be described as being made from renewable materials. It is important to recognise that a narrow focus to research development goals, or poorly executed product design, can lead to bio-based products that may not themselves actually be renewable, nor possible to recirculate the material resource in a circular economy. The following examples of chemistry offer an indication of the measures required to ensure recycled and renewable materials are valued and not wasted.

When attempting to produce conventional products from biomass, feedstock selection is influenced by any limitations to the available technology. Green chemistry metrics (typically equations for calculating waste) help quantify this,[69] but in reality much more information is needed for a comprehensive life cycle assessment (LCA).[70] Recently a detailed analysis has shown that the environmental impact of bio-based hexamethylenediamine (HMDA, the precursor to nylon-6,6) is greater than its petrochemical equivalent and the economic benefit is lower (Scheme 3).[71] Cultivation of a food crop for the starch feedstock, and even simple processes such as steam heated drying incur large energy and emission penalties. It is therefore important to be able to appreciate the efficiency with which biomass is produced, transformed, and then used,[72] and whether it is too energy intensive or wasteful to be regarded as the basis of a sustainable manufacturing process.



Scheme 3. Simplified synthetic routes to hexamethylenediamine (HMDA) from bio-based 5-(hydroxymethyl)furfural (HMF) or 1,3-butadiene.

Life cycle assessment is not often applied to laboratory scale chemistry, but the same LCA principles that can be used to describe biomass production and chemical manufacturing can be used to equal effect in research and development situations.[73] Instead it is more common to see ‘green’ organic synthesis being practiced, justified by the replacement of hazardous chemicals, the optimisation of new and efficient alternative technologies, and quantifying waste reduction.[74] This research drive is helping to accomplish the synthesis and manufacture of many bio-based chemicals to replace equivalent petrochemical products,[75] as already shown for HDMA, and other so-called green chemicals. Unfortunately a retrospective LCA often casts doubt over new, and presumed green, chemical products,[71,76] hinting that the quite agreeable research goals of green chemistry do not always go far enough. The early implementation of LCA to guide chemical process development must become more common so not to slow the development of a circular economy. Greater training and expertise in LCA is certainly needed and would be warmly welcomed by the chemical sector.

An important aspect to the assessment of the environmental benefits of bio-based products is the location of the biomass and its proximity to the associated chemical processing plants. It is nonsensical to transport large volumes of low value biomass across long distances as happens today,[77] although the fact that this is common practice demonstrates it is economical. Depending on how a product is used the transportation of the raw material is not often a major contributor to overall life cycle impacts. The improving social-economic conditions in developing countries is changing the distribution of global demand for energy and chemicals, providing another reason to reconsider the locations and design of chemical manufacturing sites. At the moment manufacturing is often in the right place (near excellent biomass resources and fast growing markets) but for the wrong reasons (cheap labour and relaxed environmental protection regulations). We can no longer hold the view that polluting practices can be exported out of North America and Europe. As developing countries become more prosperous, demands for tighter environmental protection to be enforced should increase. There is a possibility that more manufacturing will then move to Africa, but after that there will be nowhere else to go in the search for cheap production of chemicals and other goods. The designers and engineers of new plants and processes should now place the preservation of water, soil, and air quality at the forefront of their ambitions. Traditional biomass processing operations in developed countries such as paper mills are real possibilities in this regard given their location next to large (and presumably sustainably managed) forests, the existing manufacturing and transportation infrastructure around them, and the fact that the demand for newsprint in traditional markets is declining leaving the mills open to alternative manufacturing possibilities.[78]

The full concept describing the recirculation of resources has been represented as the following diagram, consistent with the EU waste hierarchy but emphasising the return to use of materials embodied in functional products (Figure 6). Conceptually the cycle of Figure 5 is completed through the management of sustainable feedstocks and responsible land use. In summary, reuse through refurbishment and remanufacture is the most direct cycle. Reuse maintains the form of the article and so the energy input originally required to make the product is not squandered after one use (Table 2). Mechanical recycling deconstructs each article but the chemical composition is retained (*e.g.* used PET bottles are melted and extruded into PET pellets). Reshaping the recyclate into new products requires energy, but there is a potential advantage in that there is now flexibility with respect to the end product, a choice which could be market driven. Biological recycling (either composting or ultimate biodegradation in the environment) renews a bio-based feedstock in the sense that a carbon balance is restored. Thus recirculation is the complete return to use of the material resource that comprises a product, by anthropogenic or natural proceses, and without waste.[79] The order of preference for end-of-life options is dictated by the value of the material, as governed by its form and available function.

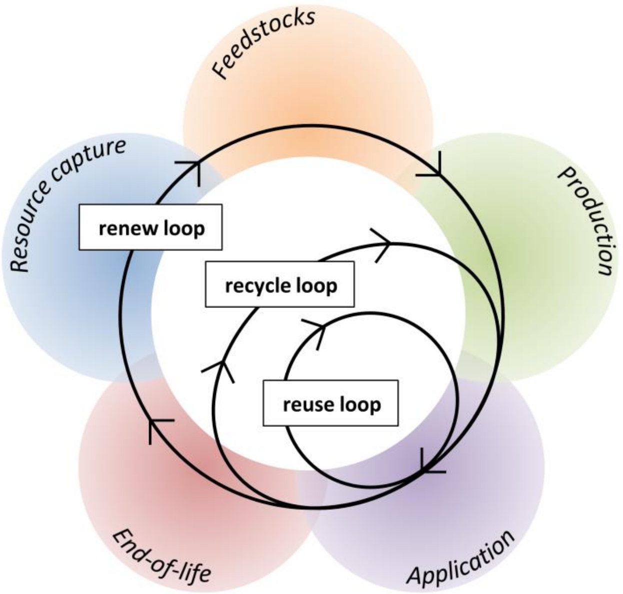


Figure 6. Chemical product cradle-to-cradle life cycle stages in a circular economy.

Sometimes there is a temptation to assume a substance or material is biodegradable or recyclable (amongst other claims) without an actual demonstration how efficiently this occurs and under what conditions. Researchers should also consider in detail the legislative field that controls the intended applications of their products. A good example of product design for optimum recycling in line with regulation comes from the natural fiber composites of Bourmaud and co-workers,[80] who have shown a thorough knowledge of the applied aspects of their research. By conducting the relevant tests, they were able to prove their materials are recyclable as is required for the disassembly and recovery of end-of-life vehicles and their components by EU law.[81] These polypropylene-hemp fiber composites are therefore shown to be a viable commercial product for the automotive sector and not just an academic curiosity. A new proposal from the EC has been made to shift the current emphasis on the recycling of vehicle parts (and waste EEE) to refurbishment in order to better preserve the value of the functional parts.[82] This calls for new innovations as the circular economy comes into force.

When developing new materials such as bio-plastics and their composites,[83] the product design must balance the anticipated number of recycling loops with optimum performance and lifespan. For research and development scientists this may mean conducting mechanical recycling testing for example, probably through a collaborative research effort that may have otherwise been overlooked in preference of other pursuits. The choice of materials used in a product should reflect a preference to reuse and recycle, and combining materials with different lifespans and end-of-life management pathways should be avoided where possible, as it may unnecessarily shorten the time to product redundancy or interfere with recycling procedures.

Although it is far from instantaneous, the main purpose of biodegradation is to prevent waste and pollution, which along with resource preservation is the basic objective of a circular economy. Biodegradation should only be considered for products that cannot be effectively reused or recycled to retain their value. The need to design certain products to biodegrade may be linked to their function, or indeed user habits. A controversial aspect of this argument is plastic waste. While we endeavour to recycle (mostly petrochemical derived) plastics,[84] in reality large volumes are disposed of, which has led to alarming pollution problems and issues for a circular economy.[3,85] For instance microplastics in the oceans are hugely damaging.[86] The articles associated with marine activities will often contain non-recoverable substances (*e.g.* antifouling agents and paints for boat hulls, as well as sea fishing equipment), and must be designed to biodegrade for the sake of the environment and a circular economy. Otherwise plastic pollution is the result of industrial and municipal practices and consumer attitudes to waste. Strategies to combat plastic pollution in marine environments are ongoing.[87]

If we are not capable of recycling materials then it may be that they should be bio-based and biodegradable, despite the loss of function and therefore value incurred. Biodegradable plastics have been viewed in the past as a solution to the contribution of plastics towards landfill.[83,88] However it must be said that although recycling rates for plastics are lower than what is actually possible,[89] this is not because of inherently insurmountable technical issues. In this case introducing greater biodegradability into plastics will not encourage less waste, and where there are ways to preserve the chemical structure of the plastic by recycling, these approaches need to be encouraged. Here policy and communication, incentives and responsibility must go hand-in-hand with intelligent product design to meet European targets for higher rates of recycling.[35,90]

Europe's circular economy strategy features a binding target of no more than 10% of waste entering landfill by 2030.[1] Meanwhile waste incineration has become an increasingly popular way of eliminating landfill while generating energy in the process. Sweden for example actually imports waste to convert into energy through incineration.[91] Despite the waste treatment aspect, energy recovery from waste formed of petrochemical products should not be considered as contributing to a true circular economy. An energy intensive manufacturing process for a low value product only succeeds with the availability of cheap fuel. Cement kilns favour carbon rich fuels because they require an extremely hot flame to melt the precursor minerals and cause them to react. Solvents are one type of product that are typically viewed as a post-application fuel for cement kilns. Commercial demands and government policies that advocate energy production through waste incineration not only promote growth in an industry that thrives on abundant, low value waste, but in treating waste as a feedstock for energy actually encourages material wastefulness. This is contrary to the objective of a circular economy, despite more sympathetic accounts in the literature.[92] The push factor to reduce landfill for environmental reasons is matched by the economic pull of the energy market, and in much the same way as planned obsolescence was implemented to create wealth, the broader long term impact of the policy was not fully considered.

It can be argued that carbon capture after waste incineration of non-biomass derived products fulfils the definition of recirculation proposed here, but only if the carbon is retained in a reusable form. Despite the added benefit of energy recovery absent when bio-based products are biodegraded, conversion of the captured carbon dioxide into chemical intermediates is not trivial, and despite its obvious potential can have a significant environmental impact depending on product selection.[93] Sequestering of CO_2 is not consistent with a circular economy because this equates to a loss of resource,[94] creating a waste in a form with no value. Besides, investing and managing carbon sequestration for its own sake without development of chemical or fuel production from the captured CO_2 is not profitable, and recently the approach has faltered in the UK because of negative policy decision making regarding low carbon energy.[95]

Options for carbon capture and utilisation (CCU) fall into 3 categories: direct use of CO_2 after separation,[96] biological transformation, and chemical synthesis. The direct use of captured CO_2, as a supercritical solvent for example, is now routine and diversifying into varied applications.[97] Algae are able to convert the carbon dioxide from flue gases into chemical products,[98] and recently it has been shown that catalysts based on the abundant metal aluminum can convert the carbon dioxide in waste flue gases into cyclic carbonates, which find use as the electrolytes of lithium ion batteries and as precursors to polycarbonate plastics.[99]

If a polycarbonate made from captured CO_2 and other recirculated feedstocks could be incinerated to produce energy, and the resulting carbon dioxide captured and utilised again in the same fashion, that manufacturing and waste disposal infrastructure would lend itself to the concept of a circular economy. A possible example takes limonene, an alkene and the major component of the essential oil of citrus fruits,[100] to form a renewable polycarbonate or polyurethane upon reaction with carbon dioxide.[101]

The related idea of a methanol economy has been proposed by Nobel Prize winner George Olah, where methanol is used as a fuel, manufactured from the carbon dioxide emissions created by burning that methanol (Figure 7).[102] This is a tight, fuel orientated recirculation cycle, but as with the production of plastics from captured carbon dioxide, the concept should be considered as a valuable approach for the control of GHG emissions, and for the production of commodity chemical products (*i.e.* methanol) without a net depletion of resources. The conversion of atmospheric CO_2 into methanol is an especially interesting development in this field.[103]

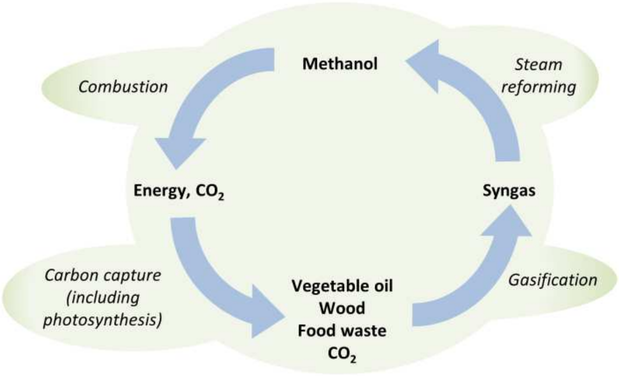


Figure 7. A schematic of the material flow in a methanol energy economy.

4. Scientific innovation enabling the circular economy

New technologies that assist the recycling of products are highly valuable of course, but typically the approach is too often segmented into the classic "problem-solution" inventive steps. Redesign of a product to be more easily and comprehensively recirculated is a much better approach to a circular economy, in effect eliminating the problem rather than having to find a solution. An intriguing example of this design issue is found in liquid crystal display (LCD) screens. Before proper legislative measures were put in place, electrical and electronic equipment (EEE) was routinely sent to landfill because it was too difficult to extract value from it once disposed of.[104] Even now after bans on the export of hazardous waste to developing countries,[105] and the EU waste EEE directive,[106] because of the continued difficulty in processing LCD screens and other EEE waste streams, illegal shipments of this resource are still made to developing countries as scrap.[107] The release of toxic chemicals from unregulated EEE waste processing has created a shocking environmental health and safety issue in these regions, where vulnerable people are compelled by financial reasons to attempt such practices, and too often without any protective equipment or formal training.[107,108] This fact is recognised by the EC in the new circular economy action plan.[2,3]

As expected, the original design of LCD equipment has much to do with the ability to then recycle it at the end of its useful functional life. Thin, yet composed of several layers containing many different materials (Figure 8),[109,110] only recently has the automated disassembly of LCD televisions been technologically achievable.[111] The EU Ecolabel certification created an incentive to redesign televisions in order to make disassembly for recycling effective,[112] and nurtured progress in simplifying the recycling of LCD equipment by removing the hazardous substances that complicate safe disposal.[113] Although the EU Ecolabel instructions require that televisions are designed for easy disassembly, and the use of toxic substances is controlled, mercury is still permitted in fluorescent lamps. Furthermore the EU Ecolabel is not mandatory, but progress towards a circular economy will require these sorts of stringent product design requirements to be more widely adopted.

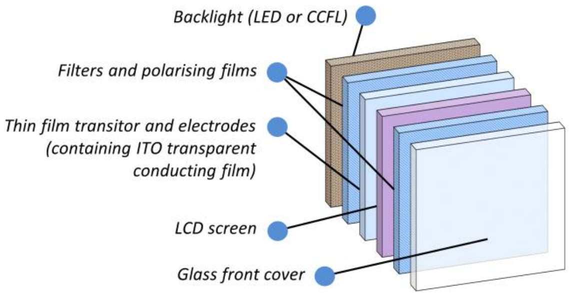


Figure 8. A simplified, exploded diagram of the layers in a LCD screen.[109,114]

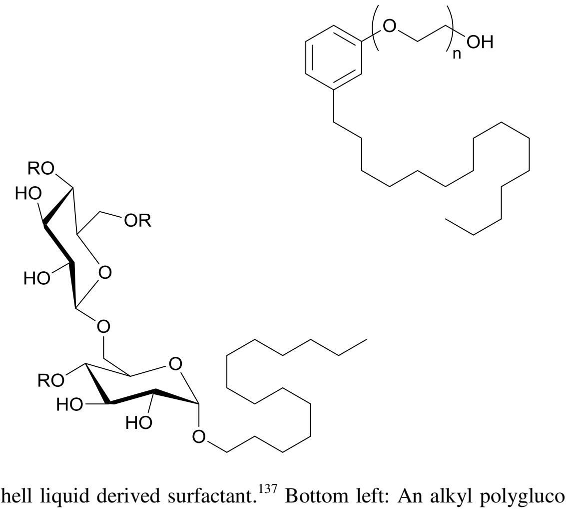
Scientific innovations now permit the extraction of liquid crystals from displays,[115] and the removal of indium metal from backing films.[116] Both processes certainly complement the mechanical recycling procedures now in place with the primary aim of metal recovery, plastic recycling and correct mercury disposal,[113,117] However, it would be far preferable to not have any toxic mercury or rare and expensive indium in the product in the first place. Improving technology in the LCD sector now means that a significant proportion of screens are now lit by LEDs,[114] and no longer require mercury containing cold-cathode fluorescent lamps (CCFLs). Light emitting diodes (LEDs) can be recycled and are covered by the EU waste EEE directive.[106] The latest advance in organic LEDs (OLEDs) is presently limited to premium LCD products, and research is ongoing to improve fabrication and performance of long lived and energy efficient devices.[118] A greater understanding of how to best design OLEDs on a molecular basis is still being established,[119] but much more work on optimal design for reuse and recycling needs to be initiated.

Organic LED displays require an indium tin oxide (ITO) transparent conducting film electrode just as standard LED displays do. Indium is on the EU critical raw materials list,[120] and as such greater efforts to limit our dependence on this metal are needed. Graphene has been proposed as an alternative material to replace ITO.[121] Advantages in a life cycle context have been calculated to be in favour of graphene, an important step in establishing the basis of research in this field.[122] Nevertheless we must be careful to consider the broadest implications of any new manufacturing process, with graphene often produced using reprotoxic solvents that may soon have REACH enforced restrictions imposed on them.[123]

The contrast between end-of-pipe waste treatment and practices inherently designed to adhere to the circular economy concept can also be found in the textile dyeing industry. The waste water produced from the dyeing of clothes is extremely voluminous, and creates pollution in places where communities are not protected by environmental regulations.[124,125] Water purification using membrane technology,[126] complements chemical and biological waste water treatments, and advantageously is not consumed in the purification process, even allowing for reclamation and reuse of waste water and the chemicals retrieved from it.[124] Mesoporous carbon supports for photocatalytic purification of water,[127] or simply used as a reversible solid absorption medium,[128] may represent an advance in this technology but the fundamental problem of the water pollution still persists. Ironically membrane fabrication is itself a source of water pollution,[129] emphasising the need for a broad analysis of all potential benefits and risks when 'green' technologies are introduced.

The latest advances in the textile industry have sought to completely eliminate water use from dyeing processes. It is estimated that 12% to 40% of the dye used in textile manufacturing ends up being washed into effluent, which amounts to 40 liters or more for every kilogram of textiles produced.[124,130] Waterless dyeing using supercritical carbon dioxide drying represents one advance that helps prevent the contamination of water in this way.[131] It is feasible that the carbon dioxide might be recycled on site as is the case for supercritical CO_2 extractions and chromatography.[132] Alternative solutions will also be needed that can drop into the existing infrastructure with immediate effect. To this end, organic solvent systems have been found that can replace water. Used in a fully recyclable system, dimethyl sulfoxide dyeing resulted in a 99% reduction in waste, as well as superior dye stability and no need for additional inorganic salts.[133] Ionic liquids can also be used in dyeing, and the addition of 1-(2-hydroxyethyl)-3-methylimidazolium chloride to the dye bath is proven to eliminate color leaching into the wash water, preventing aqueous pollutants from ever occurring.[134]

The waste water of textile dyeing is a preventable environmental hazard, but sometimes waste cannot be avoided. Furthermore, in some cases formal waste collection and recycling is also not feasible. To make matters worse, detergents for example also tend to have a very short functional lifespan. Surfactants enter the aqueous environment immediately after use, especially in the case of household cleaning products, and so the only option for recirculation within the concept of a circular economy is for biodegradation.[135] Some conventional surfactants do break down in wastewater treatment plants, but the decomposition products can be alarmingly toxic.[136] The problem of designing surfactants to biodegrade rapidly and completely to carbon dioxide and other innocuous chemicals is therefore more challenging and complex than might first be anticipated. To improve the environmental impact of aqueous cleaning products, scientists are now developing biodegradable bio-based surfactants from the oils of waste cashew nut shells,[137] and other renewable chemical intermediates (Scheme 4).[138] One of the most promising classes of bio-surfactant would seem to be the alkylpolyglucosides, where the partnership of a hydrophilic sugar group and a hydrophobic vegetable oil derived alkyl chain results in a versatile, bio-based surfactant that biodegrades completely to water and CO_2 in a period of 3 weeks.[139] Used cooking oil is a suitable feedstock from which to produce surfactants with a reduced environmental impact. This is consistent with current EU management practices where through a defined specification an application can be found for waste materials to extend and increase its function and therefore value as a material resource.[140]



Scheme 4. Top right: A cashew nut shell liquid derived surfactant.[137] Bottom left: An alkyl polyglucoside made from glucose and a fatty alcohol (R = H or glucose).[138]

An example of a successful collaboration between a manufacturer and scientists, of the sort vital to the success of the circular economy, is the discovery of switchable adhesives for carpet tiles.[141] The quantity of post-consumer carpet waste created each year is estimated to be in excess of 4 million tonnes.[142] Introducing switchable adhesives is different from an end-of-pipe recycling solution because now the product is inherently designed to make disassembly and recycling possible with the use of innovative chemicals. The binder between the carpet fibers and the bitumen backing is made from acetylated starch (Figure 9). It can be controllably deactivated with a mild alkali solution, allowing for the separation of the carpet tile components. The carpet fibers can then be recycled,[143] and the backing remanufactured into more carpet tiles. By implementing extended producer responsibility, the service of the product is valued above the materials, which are recycled into new carpet tiles.[144] The presence of the starch based adhesive advantageously eliminated the need for added brominated flame retardants with known environmental and health risks. Removing the need for these hazardous components means the recycled materials from the used carpet tiles can be processed more effectively, and not risk landfill because they do not meet chemical legislation requirements and other quality controls regarding the handling of hazardous waste.

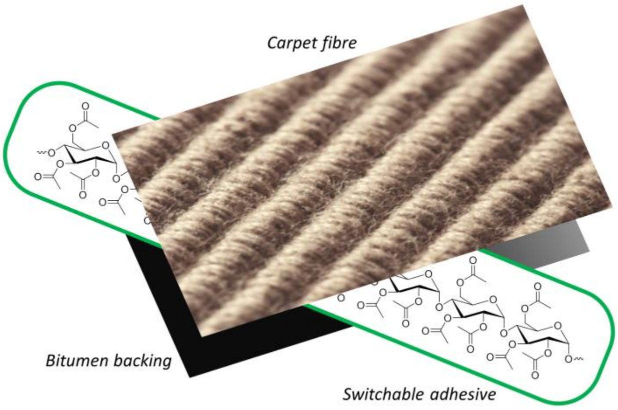


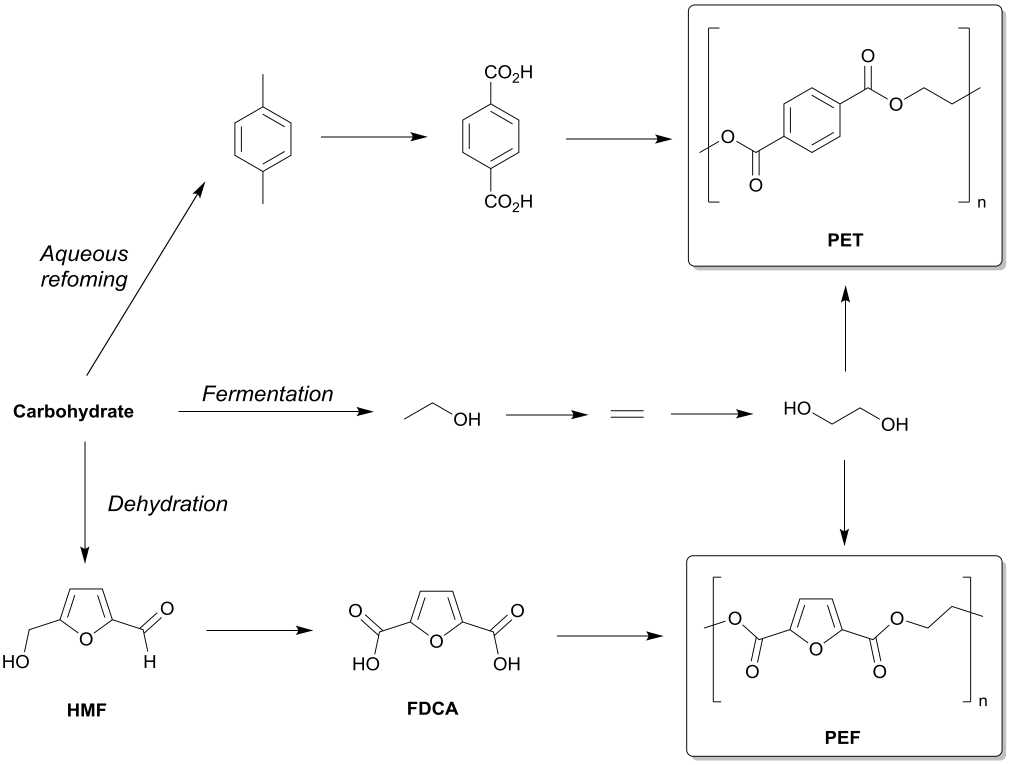
Figure 9. A simplified representation of the main layers in a switchably fixed carpet tile.

Research into bio-based polymers is a huge area of interest, with rapid projected market growth backed by legislation in France for example.[145] The sustainability of plastics has been widely studied in the literature. The main conclusions are that the scope of each LCA assessment is important and should fully embrace end-of-life considerations.[146] This is where a significant portion of global warming potential associated with plastics is found. The present-day quantity of bio-based polymers in use restricts opportunities for mechanical recycling and so biodegradation or incineration is often preferred. Recycling would reduce the carbon dioxide emissions associated with polylactic acid (PLA) disposal for instance, as well as create energy savings because the synthesis of virgin polymer is avoided.[147] It has been shown that the technologies and chemical auxiliaries used in bio-based polymer production could also be improved to reduce environmental impact.[148] Even so, present day bio-based polymer manufacturing has a similar impact to petrochemical polymer synthesis, with room to improve for this emerging bio-based industry.[146,149] Further recommendations for improving the sustainability of bio-based plastics have been suggested by Álvarez-Chávez *et al*., and include the use of wastes and by-products as feedstocks, safer additives, water recycling in manufacturing plants, and avoiding composites with petrochemical polymers that reduce overall biodegradability.[148]

Life cycle assessments have produced some surprising conclusions regarding the optimum material and disposal options for different items of packaging. Food packaging is a sensitive subject because hygiene and food quality cannot be compromised, yet there is an overwhelming pressure to reduce packaging. If the poor performance of the packaging increases the likelihood of food waste, then the environmental impact of the surplus food production can overshadow that of the packaging. Lightweight,[150] and recyclable,[151] packaging is environmentally superior to typical multilayer alternatives if considered in isolation. However if the probability of any food loss incurred because of inferior packaging is also considered, the environmental burden of agriculture can reveal easily recyclable, lightweight monolayer packaging to be unfavourable.[152]

Polylactic acid (PLA) is one of the most prominent synthetic bio-based polymers and generally performs well in comparative LCAs against fossil derived plastics.[148,153] Although it now features in several types of plastic product (including food packaging) PLA nevertheless has some notable disadvantages to overcome with respect to its limited mechanical properties and thermal stability.[154] It is also crucial to appreciate that PLA is only biodegradable in an industrial composting setting. The lower temperatures of home composting units are unsuitable and will reduce the quality of the compost.[88] Supposedly biodegradable polymers can be persistent in the environment in the absence of correct end-of-life management, which is obviously a risk to a circular economy.[155] Therefore more information must be communicated with new products to help them reach their intended end-of-life process. The chemical components of blends and composites involving bio-based polymers should have the same intended end-of-life pathway if they cannot be separated. Unfortunately the present day recycling of composite materials can be extremely challenging.[156] Furthermore any impact of mineral fillers on biodegradation, disintegration and composting should be understood at the product design stage.[157a]

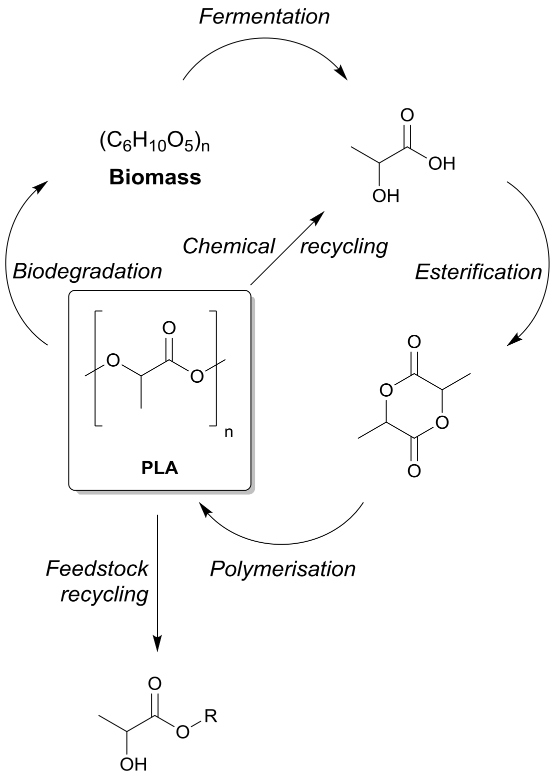
Unconventional bio-based chemicals tend to have a complementary structure to the precursor biomass, rather than sacrifice the inherent functionality of the feedstock just to replicate their crude oil derived analogues. Polylactic acid (PLA) fits this description, as it is produced from the fermentation product lactic acid. Contrastingly polyethylene terephthalate (PET) has now been made exclusively from renewable resources, but the synthesis is protracted and low yielding,[158] and can involve hazardous reagents. As a replacement for PET, polyethylene furanoate (PEF) has a more amenable chemical structure for a synthetic target produced from biomass (Scheme 5).[159] The terephthalate monomer is replaced by 2,5-furandicarboxylic acid (FDCA), which although offers some technological advantages,[160] PEF is severely restricted by the present day manufacturing scale and cost. There is a perception that PEF and other new types of emerging bio-based polyesters will contaminate PET recyclates and reduce the quality of this secondary manufacturing material.[161] A hesitance by end users of PET to make this quite major shift in material use stems from the short term uncertainty and possible negative effects that might be experienced during a transition phase. This sort of barrier to achieving longer term benefits is not a new issue and historically is overcome by the tenacity of a few proactive companies willing to spearhead change.[162]



Scheme 5. The synthesis of bio-based polyethylene terephthalate (PET) and polyethylene furanoate (PEF).

Future technological advances may open new avenues for increasingly diverse recycling methods, and this can be taken into account when developing improved chemical products for a circular economy. Although commercial realisation is strongly dependent on the scale of the available recyclate that can be processed, the development of chemical recycling is one technology that would greatly help with the recirculation of novel plastics. Chemical recycling of plastics involves a depolymerisation to return back to the monomer. This approach to closed loop recycling preserves the functionality and value of the feedstock where otherwise only open loop recycling might be feasible, or perhaps thermal instability means mechanical recycling degrades the polymer and impairs its performance in subsequent applications.[157b] In principle all polyesters can be hydrolysed or transesterified to produce monomers for the synthesis of new plastics,[163] but chemical recycling is particularly appropriate for bio-based plastics that cannot be recycled using the established means.[83] Chemical recycling of polyolefins is a less pressing issue because mechanical recycling is effective, but it is interesting for the creation of intermediates with the broader potential as a cheap chemical feedstock.[164] This sort of chemical recycling to give a less specific product stream (also known as feedstock recycling, *e.g.* gasification into synags and olefins) is appealing for mixed wastes and composites that are difficult to separate into pure waste streams.[165]

The chemical recycling of PLA is well understood, and can be applied in such a way to either return to the lactic acid or lactide pre-cursors of polymerisation, or even provide lactate esters (Scheme 6).[166] Ethyl lactate is recognised as a green solvent and is a valuable replacement for more toxic alternatives in cleaning products and formulations.[167] Other polymers suitable for chemical recycling include the polymethyl methacrylate found in LCD equipment,[168] and nylon which can be recycled using supercritical fluid solvents.[169]



Scheme 6. Chemical recycling options for PLA.

5. Outlook for a sustainable chemical industry

Research goals across the scientific disciplines have clearly been influenced in the recent past by concerns over climate change, the demand for renewable energy, sustainability and environmental protection. Now the world's need to associate a greater value to materials and the service provided by products can be considered as a topic of equal importance. In a circular economy it is not enough to just replace unsustainable feedstocks with biomass without optimising processing and product design to avoid waste and inadvertent environmental damage. Present day end-of-pipe waste management is not sufficient either, and cannot create a circular economy by itself.[170] Furthermore, present day recycling practices are not comprehensive enough in how they separate wastes to be able to achieve the complete recirculation of materials.[171] This work has described how product design, when developed in harmony with recycling practices,[172] can help achieve optimum material use and minimise waste. The efforts of product designers must be assisted by policy makers who have a responsibility to introduce quality control protocols to help direct waste into the appropriate end-of-life recirculation processes,[35,173] and yet remove the regulatory barriers to a circular economy.[174] Thus 'waste' is now the feedstock of a circular economy, reducing demand for those primary resources with an observably and worryingly finite existence. If a reuse and recycle strategy cannot be foreseen then chemicals must be designed to biodegrade, and in these cases a renewable resource is required for their synthesis. Here the recirculation of materials is shepherded by the biological processes of photosynthesis and biodegradation.

The aspirations of research and development chemists in industry and academia can be subtly tweaked to better incorporate the goals of a circular economy. At the same time there is a new responsibility on the designers of products to communicate their needs at chemical R&D level to encourage improvements in chemical synthesis and the products they make. Adopting the recommendations suggested throughout this article will help scientists future-proof their work, making it more relevant to the increasingly regulated chemical sectors and more appealing to funding bodies.

The use of environmental assessments (typified by the LCA) must become more prevalent. The benefit of LCA to guide early stage chemistry as well as identify the emissions and land use associated with large scale processes is huge. Unfortunately the availability of data is restricted and the necessary expertise is not widespread. The legislative aspect of the circular economy does not help in this respect; instead it defines ambitions and introduces the regulatory targets needed to achieve those ambitions. Some guidance on waste management and resource efficiency will be issued by the European Commission.[2] However this does not equip scientists with the tools they need to contribute to a circular economy. As a first step chemists should become more acquainted with published examples of LCA and other forms of environmental assessment (as well as complete sustainability assessments of course). From here collaboration with environmental scientists is the obvious way forward for chemists to understand the environmental implications of their research and improve process development.

Whether a scientist has ambitions of contributing to a circular economy or not, being able to demonstrate the recyclability of new products,[175] or being able to show biodegradability through standardised testing,[176] and establishing whether they are fit for REACH compliance,[177] will become important if not compulsory. The obvious choice for research scientists producing novel materials and substances is to establish strong interdisciplinary links with biodegradation labs, ecotoxicity specialists, collaborate with manufacturers, and understand the regulatory field. It is also vital to consider products in terms of the service they provide, not just in terms of chemical composition.

Generally speaking, synthetic chemists would do well to understand some of the prominent regulation, certification and labelling schemes relating to bio-based content and sustainability to guide product design. If there is an awareness of product requirements beyond direct measures of performance at an early stage of the design process, there is a better chance of achieving customer acceptance and commercial realisation. For instance, certification of bio-based content does not require the product to be entirely bio-based in origin. Usually the assessment is on the basis of carbon mass only, and the lower limit can currently be as low as 20% bio-based (carbon) content.[178] Sustainability certification, for example International Sustainability and Carbon Certification (ISCC),[179] and responsible design certification such as 'Cradle2Cradle',[180] have quite precise requirements that must be adhered to. These include bans on the inclusion of certain chemicals and the offsetting of emissions, all of which are helpful criteria to evaluate products with. New toolkits that inform users about the steps towards a circular economy are a useful educational platform also.[181]

From an industrial perspective, symbiosis,[182] where the output of one process is the input of an otherwise unrelated process, is a convenient approach to eliminating waste and primary resource demand. Particularly appealing is the use of carbon dioxide and its sequestering into the chemical structure of recirculated products.[183] The use of wastes and recycled materials might be an uncomfortable concept for research chemists who deal with pure, refined chemical intermediates, but this position is being eroded away with time as innovative examples begin to appear in the literature,[184] especially in materials science.[185] The opinion of industry is quite different, with companies increasingly looking to supplement the revenue from their traditional (and sometimes declining) business by valorising their waste stream.

To take a final example, the impact of the digital revolution on the paper and pulp industry has forced the sector to diversify its product portfolio and reduce its costs.[186] One recent advance has demonstrated the possibility to co-produce cellulose pulp (for paper production) and a valuable lignin derived oil from the waste.[187] Even sawdust from biomass pre-processing can be converted into chemical intermediates such as levoglucosenone and its downstream products for the fine chemicals sector.[188] There is a long standing environmental issue with the sulfite liquors of the pulping process,[189] but this is a resource too, and can be used as a feeedstock for microbial polyhydroxyalkanoate (PHA) production.[190] Add to this the significant recycling of paper,[191] and the paper and pulp industry appears to be moving towards a circular model.[192] The example of the paper industry demonstrates that the challenges and hence opportunities a circular economy brings to chemists are substantial, not just in their own discipline but across all the manufacturing industries and the energy sector.

Achieving maximum material recirculation will require certain practical steps to be made, such as increases to recycling capacity and stronger markets for the secondary materials it creates. Equally the transition to a circular economy is absolutely reliant on innovative technologies and improvements to how product design is viewed and executed.[3] Despite some criticism of the European circular economy political strategy,[193] economists and social scientists have taken it upon themselves to understand and define the principle with a bottom-up approach.[194] Now the stage has been set for chemistry and its associated disciplines to take advantage of an exciting revolution in chemicals and product design.[195]

References

1 European Commission circular economy strategy, http://ec.europa.eu/environment/circular-economy/index_en.htm, (accessed 11-02-2016); Closing the loop: commission adopts ambitious new circular economy package to boost competitiveness, create jobs and generate sustainable growth, http://europa.eu/rapid/press-release_IP-15-6203_en.htm, (accessed 04-12-2015).

2 European Commission circular economy package: questions & answers, http://europa.eu/rapid/press-release_MEMO-15-6204_en.htm, (accessed 04-12-2015).

3 Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, closing the loop - an EU action plan for the circular economy, http://ec.europa.eu/priorities/jobs-growth-investment/circular-economy/docs/communication-action-plan-for-circular-economy_en.pdf, (accessed 04-12-2015).

4 D. Andrews, *Local Economy*, 2015, **30**, 305; European Economic and Social Committee towards more sustainable consumption: industrial product lifetimes and restoring trust through consumer information, http://www.eesc.europa.eu/?i=portal.en.ccmi-opinions.26788, (accessed 23-11-2015).

5 A. Murray, K. Skene and K. Haynes, *J. Bus. Ethics*, 2015, DOI: 10.1007/s10551-015-2693-2.

6 J. H. Clark and F. E. I. Deswarte in *Introduction to Chemicals from Biomass*, ed. J. H. Clark and F. E. I. Deswarte, John Wiley & Sons, Chichester, 1st edition, 2008, p.1.

7 World Bank Carbon Finance Unit carbon fund for Europe, http://wbcarbonfinance.org/CFE, (accessed 23-11-2015); European Central Bank environmental protection, https://www.ecb.europa.eu/ecb/orga/escb/green/html/index.en.html, (accessed 23-11-2015); K. Cooke, Climate News Network, 21st April 2015, http://www.climatenewsnetwork.net/key-role-urged-on-central-banks-in-climate-fight, (accessed 23-11-2015); Investors welcome newly released World Bank green bond impact report, http://www.worldbank.org/en/news/feature/2015/08/11/investors-welcome-world-bank-green-bond-impact-report, (accessed 23-11-2015); Bank of England climate change adaptation reporting, http://www.bankofengland.co.uk/pra/Pages/supervision/activities/climatechange.aspx, (accessed 23-11-2015); M. Hertsgaard, Bloomberg, 26th June 2014, http://www.bloomberg.com/bw/articles/2014-06-26/climate-change-and-the-two-thirds-imperative,

(accessed 23-11-2015); J. Shankleman, The Guardian (UK, newspaper), 13th October 2014, http://www.theguardian.com/environment/2014/oct/13/mark-carney-fossil-fuel-reserves-burned-carbon-bubble, (accessed 23-11-2015); D. Carrington, The Guardian (newspaper, UK), 1st December 2014, http://www.theguardian.com/environment/2014/dec/01/bank-of-england-investigating-risk-of-carbon-bubble, (accessed 23-11-2015).

8 N. van Nes and J. Cramer, *The Journal of Sustainable Product Design*, 2003, **3**, 101.

9 European Commission circular economy strategy roadmap, http://ec.europa.eu/smart-regulation/impact/planned_ia/docs/2015_env_065_env+_032_circular_economy_en.pdf, (accessed 23-11-2015).

10 D. Buschak and G. Lay in *Servitization in Industry*, ed. G. Lay, Springer International Publishing, Cham, 2014, pp. 131-150; E. D. Reiskin, A. L. White, J. K. Johnson and T. J. Votta, *J. Ind. Ecol.*, 1999, **3**, 19.

11 M. Stoughton and T. Votta, *J. Cleaner Prod.*, 2002, **11**, 839.

12 D. Kindström, *European Management Journal*, 2010, **28**, 479.

13 A. Tukker, *J. Cleaner Prod.*, 2015, **97**, 76.

14 United Nations Industrial Development Organization chemical leasing information, http://www.unido.org/chemical-leasing.html, (accessed 02-09-2015); F. Moser, T. Jakl, R. Joas and F. Dondi, *Environ. Sci. Pollut. Res.*, 2014, **21**, 12445; R. Lozanoa, A. Carpenter and F. J. Lozano, *Resour. Conserv. Recycl.*, 2014, **86**, 53.

15 F. Moser and T. Jakl, *Environ. Sci. Pollut. Res.*, 2015, **22**, 6325.

16 Chemical Strategies Partnership, *Tools for optimizing chemical management*, CSP, San Francisco, 1999.

17 L. Stringer, The Guardian (newspaper, UK), 9th December 2014, http://www.theguardian.com/sustainable-business/2014/dec/09/chemical-leasing-ecolab-coke-ikea-gm-un-cleaning-environment, (accessed 23-11-2015).

18 K. Intlekofer, B. Bras and M. Ferguson, *Environ. Sci. Technol.*, 2010, **44**, 4409; V. V. Agrawal, M. Ferguson, L. B. Toktay and V. M. Thomas, *Management Science*, 2012, **58**, 523; Towards the circular economy: opportunities for the consumer goods sector, http://www.ellenmacarthurfoundation.org/assets/downloads/publications/TCE_Report-2013.pdf, (accessed 24-11-2015).

19 Organization for Economic Cooperation and Development (OECD), *Extended producer responsibility: a guidance manual for governments*, OECD, Paris, 2001; S. Retzén and C. Beskow, *The Journal of Sustainable Product Design*, 2001, **1**, 91; Time to redesign extended producer responsibility for a circular economy, http://www.zerowasteeurope.eu/2015/07/time-to-redesign-extended-producer-responsibility-for-a-circular-economy-new-study-from-zero-waste-europe, (accessed 23-11-2015); A. Pires, G. Martinho, R. Ribeiro, M. Mota and L. Teixeira, *J. Cleaner Prod*., 2015, **108**, 343; A. Massarutto, *Resour. Conserv. Recycl.*, 2014, **85**, 11; S. Niza, E. Santos, I. Costa, P. Ribeiro and P. Ferrão, *J. Cleaner Prod.*, 2014, **64**, 277.

20 British Standard BS 8887-1, *Design for manufacture, assembly, disassembly and end-of-life processing (MADE) - General concepts, process and requirements*, BSI, London, 2006.

21 Building blocks of a circular economy, http://www.ellenmacarthurfoundation.org/circular-economy/building-blocks, (accessed 23-11-2015).

22 WRAP's vision for the UK circular economy to 2020, http://www.wrap.org.uk/content/wraps-vision-uk-circular-economy-2020, (accessed 23-11-2015).

23 Towards the circular economy: economic and business rationale for an accelerated transition, http://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf, (accessed 24-11-2015).

24 J. A. Matthews and H. Tan, *Nature*, 2016, **531**, 440; B. Su, A. Hesmati, Y. Geng and X. Yu, *J. Cleaner Prod.*, 2013, **42**, 215.

25 Achieving a circular economy: how the private sector Is reimagining the future of business, https://www.uschamberfoundation.org/sites/default/files/Circular%20Economy%20Best%20Practices.pdf, (accessed 23-11-2015).

26 S. Sauvé, S. Bernard and P. Sloan, *Environmental Development*, 2015, DOI: 10.1016/j.envdev.2015.09.002.

27 M. J. Boss, B. Boss, C. Boss, D. W. Day and J. Wang in *Handbook of Chemical Regulations: Benchmarking, Implementation, and Engineering Concepts*, Ed. M. J. Boss, B. Boss, C. Boss and D. W. Day), CRC Press, Boca Raton, 2015, pp. 1-12; P. Fisk, *Chemical Risk Assessment: A Manual for REACH*, John Wiley and Sons, Chichester, 2014.

28 J. M. Fraile, J. I. García, C.I. Herrerías, J. A. Mayoral, E. Pires and L. Salvatella, *Catal. Today*, 2009, **140**, 44; A. P. Wight and M. E. Davis, *Chem. Rev.*, 2002, **102**, 3589.

29 M. Heitbaum, F. Glorius and I. Escher, *Angew. Chem. Int. Ed.*, 2006, **45**, 4732.

30 T. Banno, H. Sato, T. Tsuda and S. Matsumura, *J. Oleo Sci.*, 2011, **60**, 117.

31 D. J. C. Constable, *Aldrichimica Acta*, 2015, **48**, 7.

32 E. S. Beach, Z. Cui and P. T. Anastas, *Energy Environ. Sci.*, 2009, **2**, 1038.

33 Regulation (EC) 1907/2006 of the European Parliament and of the Council of 18th December 2006, *Concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC*, 2006.

34 A. Lagerkvist, H. Ecke and T. H. Christensen, in *Solid Waste Technology and Management Vol. 1*, ed. T. H. Christensen, John Wiley and Sons, Chichester, 2011, pp. 63-84.

35 Directive 2008/98/EC of the European Parliament and of the Council of 19th November 2008, *On waste and repealing certain Directives*, 2008.

36 The social benefits of a circular economy: lessons from the UK, http://www.green-alliance.org.uk/resources/The%20social%20benefits%20of%20a%20circular%20economy.pdf, (accessed 23-11-2015).

37 European Commission proposal for a Directive of the European Parliament and of the Council amending Directive 2008/98/EC on waste, http://ec.europa.eu/priorities/jobs-growth-investment/circular-economy/docs/amending-directive-waste_en.pdf, (accessed 04-12-2015).

38 B. K. Reck and T. E. Graedel, *Science*, 2012, **337**, 690.

39 J. Suckling and J. Lee, *Int. J. Life Cycle Assess.*, 2015, **20**, 1181.

40 T. Zink, F. Maker, R. Geyer, R. Amirtharajah and V. Akella, *Int. J. Life Cycle Assess.*, 2014, **19**, 1099.

41 P. Tanskanen, *Acta Mater.*, 2013, **61**, 1001.

42 J. R. Dodson, A. J. Hunt, H. L. Parker, Y. Yang and J. H. Clark, *Chemical Engineering and Processing: Process Intensification*, 2012, **51**, 69.

43 A. J. Hunt, T. J. Farmer and J. H. Clark in *Elemental Recovery and Sustainability*, Ed. A. J. Hunt, RSC, Cambridge, 2013, p. 3.

44 The chemical elements of a smartphone, http://www.compoundchem.com/2014/02/19/the-chemical-elements-of-a-smartphone, (accessed 23-11-2015).

45 M. Patel, M. Crank, V. Dornburg, B. Hermann, L. Roes, B. Hüsing, L. Overbeek, F. Terragni and E. Recchia, *Medium and Long-Term Opportunities and Risk of the Biotechnological Production of Bulk Chemicals from Renewable Resources - The Potential of White Biotechnology*, 2006. Available online at http://www.bio-economy.net/applications/files/Brew_project_report.pdf, (accessed on 16-06-2015).

46 C. B. C. Raj, N. Ramkumar, A. H. J. Siraj and S. Chidambaram, *Process Saf. Environ. Prot*., 1997, **75**, 245.

47 J. H. Clark, T. J. Farmer, A. J. Hunt and J. Sherwood, *Int. J. Mol. Sci.*, 2015, **16**, 17101.

48 B. M. Trost, *Acc. Chem. Res.*, 2002, **35**, 695.

49 R. A. Sheldon, *Catal. Today*, 2011, **167**, 3; K. Iffland, J. Sherwood, M. Carus, A. Raschka, T. Farmer and J. Clark, *Definition, Calculation and Comparison of the "Biomass Utilization Efficiency (BUE)" of Various Bio-based Chemicals, Polymers and Fuels*, nova-Institut GmbH, Huerth, 2015. Available online at http://bio-based.eu/?did=32321&vp_edd_act=show_download, (accessed 19-02-2016).

50 S. Cadoux, A. B. Riche, N. E. Yates and J. -M. Machet, *Biomass Bioenergy*, 2012, **39**, 14.

51 J. Philp, *Energy Environ. Sci.*, 2015, **8**, 3063.

52 Building a high value bioeconomy, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/408940/BIS-15-146_Bioeconomy_report_-_opportunities_from_waste.pdf, (accessed 24-11-2015).

53 J. S. Golden and R. B. Handfield, *Opportunities in the Emerging Bioeconomy*, 2014. Available online at http://www.biopreferred.gov/files/WhyBiobased.pdf, (accessed 24-11-2015); J. S. Golden, R. B. Handfield, J. Daystar and T. E.

McConnell, *An Economic Impact Analysis of the U.S. Biobased Products Industry: A Report to the Congress of the United States of America*, 2015. Available online at http://bbia.org.uk/wp-content/uploads/2015/06/EconomicReport_6_12_2015.pdf, (accessed 24-11-2015).

54 C. S. K. Lin, L. A. Pfaltzgraff, L. Herrero-Davila, E. B. Mubofu, S. Abderrahim, J. H. Clark, A. A. Koutinas, N. Kopsahelis, K. Stamatelatou, F. Dickson, S. Thankappani, Z. Mohamed, R. Brocklesby and R. Luque, *Energy Environ. Sci.*, 2013, **6**, 426; J. H. Clark, L. A. Pfaltzgraff, V. L. Budarin, A. J. Hunt, M. Gronnow, A. S. Matharu, D. J. Macquarrie and J. R. Sherwood, *Pure Appl. Chem.*, 2013, **85**, 1625; A. Jurgilevich, T. Birge, J. Kentala-Lehtonen, K. Korhonen-Kurki, J. Pietikäinen, L. Saikku and H. Schösler, *Sustainability*, 2016, **8**, 69.

55 H. C. Kolb, M. G. Finn and K. B. Sharpless, *Angew. Chem. Int. Ed.*, 2001, **40**, 2004; R. A. Sheldon, *Chem. Soc. Rev.*, 2012, **41**, 1437.

56 S. Wang, *Environ. Sci. Technol.*, 2008, **42**, 7055; I. Bauer and H. -J. Knölker, *Chem. Rev.*, 2015, **115**, 3170.

57 Y. Ni, D. Holtmann and F. Hollmann, *ChemCatChem*, 2014, **6**, 930; A. Wells and H. -P. Meyer, *ChemCatChem*, 2014, **6**, 918; C. M. Clouthier and J. N. Pelletier, *Chem. Soc. Rev.*, 2012, **41**, 1585; A. Illanesa, A. Cauerhff, L. Wilson and G. R. Castro, *Bioresour. Technol.*, 2012, **115**, 48.

58 P. J. Dunn, S. Galvin and K. Hettenbach, *Green Chem.*, 2004, **6**, 43.

59 N. B. Pramanik, G. B. Nando and N. K. Singha, *Polymer*, 2015, **69**, 349.

60 United Nations sustainable development goals, http://www.un.org/sustainabledevelopment/sustainable-development-goals (accessed 18-04-2016); M. Eissen, J. O. Metzger, E. Schmidt and U. Schneidewind, *Angew. Chem. Int. Ed.*, 2002, **41**, 414.

61 European Standard EN 15343, *Plastics – Recycled plastics – Plastics recycling traceability and assessment of conformity and recycled content*, BSI, London, 2007; European Standard EN 13437, *Packaging and material recycling – Criteria for recycling methods – Description or recycling processes and flow charts*, BSI, London, 2003.

62 F. P. La Mantia, L. Botta, M. Morreale and R. Scaffaro, *Polym. Degrad. Stab.*, 2012, **97**, 21; S. M. Dolores, A. M. Patricia, F. Santiago and L. Juan, *J. Appl. Polym. Sci.*, 2014, **131**, 41161.

63 R. Luther in *Lubricants and lubrication*, Ed. T. Mang and W. Dresel, Wiley-VCH, Weinheim, 2nd edition, 2007, pp. 119-182.

64 J. Martínez-Blanco, C. Lazcano, T. H. Christensen, P. Muñoz, J. Rieradevall, J. Møller, A. Antón and A. Boldrin, *Agron. Sustainable Dev.*, 2013, **33**, 721.

65 J. Salimon, N. Salih and E. Yousif, *Eur. J. Lipid Sci. Technol.*, 2010, **112**, 519.

66 European Commission 2020 climate and energy package, http://ec.europa.eu/clima/policies/strategies/2020/documentation_en.htm, (accessed 23-11-2015).

67 G. J. Youinou, *Renewable Sustainable Energy Rev.*, 2016, **53**, 1626.

68 Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009, *Establishing a framework for the setting of ecodesign requirements for energy-related products*, 2009.

69 C. R. McElroy, A. Constantinou, L. C. Jones, L. Summerton and J. H. Clark, *Green Chem.*, 2015, **17**, 3111.

70 D. Kralisch, D. Ott and D. Gericke, *Green Chem.*, 2015, **17**, 123.

71 A. B. Dros, O. Larue, A. Reimond, F. De Campo and M. Pera-Titus, *Green Chem.*, 2015, **17**, 4760.

72 H. H. Khoo, W. L. Ee and V. Isoni, *Green Chem.*, 2016, DOI: 10.1039/C5GC02065D.

73 X. Domènech, J. A. Ayllón, J. Peral and J. Rieradevall, *Environ. Sci. Technol.*, 2002, **36**, 5517.

74 B. H. Lipshutz, N. A. Isley, J. C. Fennewald and E. D. Slack, *Angew. Chem. Int. Ed.*, 2013, **52**, 10952.

75 R. A. Sheldon, *Green Chem.*, 2014, **16**, 950; C. H. Christensen, J. Rass-Hansen, C. C. Marsden, E. Taarning and K. Egeblad, *ChemSusChem*, 2008, **1**, 283.

76 Y. Zhang, B. R. Bakshi and E. S. Demessie, *Environ. Sci. Technol.*, 2008, **42**, 1724.

77 UK's renewable energy targets drive increases in U.S. wood pellet exports, http://www.eia.gov/todayinenergy/detail.cfm?id=20912, (accessed 23-11-2015); Stolen goods: the EU's complicity in illegal tropical deforestation, http://www.fern.org/stolengoods, (accessed 16-02-2016).

78 R. Bolger, ABC news, 13th November 2015, http://www.abc.net.au/news/2015-11-13/tasmanias-new-multi-billion-dollar-green-chemical-industry/6939522, (accessed 24-11-2015).

79 J. H. Clark, T. J. Farmer, L. Moity and J. Sherwood, *Definitions for renewable elements and renewable molecules*, 2015. Available online at http://www.biobasedeconomy.eu/wp-content/plugins/download-monitor/download.php?id=59, (accessed 24-11-2015).

80 A. Bourmaud and C. Baley, *Polym. Degrad. Stab.*, 2007, **92**, 1034; A. Bourmaud, A. Le Duigou and C. Baley, *Polym. Degrad. Stab.*, 2011, **96**, 1732.

81 Directive 2000/53/EC of the European Parliament and of the Council of 18th September 2000, *On end-of-life vehicles*, 2000.

82 European Commission proposal for a Directive of the European Parliament and of the Council amending Directives 2000/53/EC on end-of-life vehicles, 2006/66/EC on batteries and accumulators and waste batteries and accumulators, and 2012/19/EU on waste electrical and electronic equipment, http://ec.europa.eu/priorities/jobs-growth-investment/circular-economy/docs/amending-directive-batteries-electronic-waste_en.pdf, (accessed 04-12-2015).

83 A. Soroudi and I. Jakubowicz, *Eur. Polym. J.*, 2013, **49**, 2839.

84 J. Hopewell, R. Dvorak and E. Kosior, *Phil. Trans. R. Soc. B*, 2009, **364**, 2115.

85 European Environmental Bureau, Seas at Risk, Friends of the Earth joint open letter to Jean-Claude Junker, http://seas-at-risk.org/images/pdf/Letters/FINAL_letter_to_Juncker_marine_litter_target_in_CE_121115.pdf, (accessed 23-11-2015); The new plastics economy: rethinking the future of plastics, http://www.ellenmacarthurfoundation.org/publications/the-new-plastics-economy-rethinking-the-future-of-plastics, (accessed 19-02-2016); L. Hepler, GreenBiz, 3rd February 2016, http://www.greenbiz.com/article/why-materials-will-make-or-break-circular-economy, (accessed 16-02-2016).

86 C. M. Rochman, A. Tahir, S. L. Williams, D. V. Baxa, R. Lam, J. T. Miller, F. -C. Teh, S. Werorilangi and S. J. Teh, *Sci. Rep.*, 2015, **5**, 14340; S. L. Wright, R. C. Thompson and T. S. Galloway, *Environmental Pollution*, 2013, **178**, 483; M. F. Costa and M. Barletta, *Environ. Sci.: Processes Impacts*, 2015, **17**, 1868.

87 M.H. Depledge, F. Galgani, C. Panti, I. Caliani, S. Casini, and M. C. Fossi, *Mar. Environ. Res.*, 2013, **92**, 279; Directive 2008/56/EC of the European Parliament and of the Council of 17th June 2008, *Establishing a framework for community action in the field of marine environmental policy*, 2008.

88 J. H. Song, R. J. Murphy, R. Narayan and G. B. H. Davies, *Phil. Trans. R. Soc. B*, 2009, **364**, 2127.

89 European Environment Agency recycling rates in Europe, http://www.eea.europa.eu/about-us/what/public-events/competitions/waste-smart-competition/recycling-rates-in-europe/view, (accessed 23-11-2015); Eurostat packaging waste statistics, http://ec.europa.eu/eurostat/statistics-explained/index.php/Packaging_waste_statistics, (accessed 23-11-2015).

90 J. Krozer and P. Doelman, *The Journal of Sustainable Product Design*, 2003, **3**, 3.

91 M. Olofsson, J. Sahlin, T. Ekvall and J. Sundberg, *Waste Manage. Res.*, 2005, **23**, 3.

92 S. -Y. Pan, M. A. Du, I. -T. Huang, I -H. Liu, E. -E. Chang and P. -C. Chiang, *J. Cleaner Prod.*, 2015, **108**, 409.

93 R. M. Cuéllar-Franca, A. Azapagic, *J. CO2 Util.*, 2015, **9**, 82; N. von der Assen, J. Jung and A. Bardow, *Energy Environ. Sci.*, 2013, **6**, 2721.

94 F.D. Meylan, V. Moreau and S, Erkman, *J.CO2 Util.*, 2015, **12**, 101.

95 E. Stoye, Chemistry World, 28th September 2015, http://www.rsc.org/chemistryworld/2015/09/drax-pulls-out-carbon-capture-storage-power-station, (accessed 23-11-2015); BBC News, 25th September 2015, http://www.bbc.co.uk/news/business-34356117, (accessed 23-11-2015).

96 B. Singh, A. H. Strømman and E. G. Hertwich, *Int. J. Greenhouse Gas Control*, 2011, **5**, 911.

97 M. Herrero, J. A. Mendiola, A. Cifuentes and E. Ibáñez, *J. Chromatogr. A*, 2010, **1217**, 2495.

98 J. C. M. Pires, M. C. M Alvim-Ferraz, F. G. Martins and M. Simões, *Renewable Sustainable Energy Rev.*, 2012, **16**, 3043.

99 M. North, B. Wang and C. Young, *Energy Environ. Sci.*, 2011, **4**, 4163; M. North, *Chim. Oggi*, 2012, **30**, 3.

100 R. Ciriminna, M. Lomeli-Rodriguez, P. D. Carà, J. A. Lopez-Sanchez and M. Pagliaro, *Chem. Commun.*, 2014, **50**, 15288.

101 M. Bähr, A. Bitto and R. Mülhaupt, *Green Chem.*, 2012, **14**, 1447; O. Hauenstein, M. Reiter, S. Agarwal, B. Rieger and A. Greiner, *Green Chem.*, 2016, **18**, 760.

102 G. A. Olah, *Angew. Chem. Int. Ed.*, 2013, **52**, 104.

103 J. Kothandaraman, A. Goeppert, M. Czaun, G. A. Olah and G. K. S. Prakash, *J. Am. Chem. Soc.*, 2016, **138**, 778.

104 S. -K. S. Fan, C. Fan, J. -H. Yang and K. F. -R. Liu, *J. Cleaner Prod.*, 2013, **39**, 209.

105 United Nations Environment Programme Basel convention overview, http://www.basel.int/TheConvention/Overview/tabid/1271, (accessed 23-11-2015).

106 Directive 2012/19/EU of the European Parliament and of the Council of 4th July 2012, *Waste electrical and electronic equipment (WEEE)*, 2012.

107 UNEP news centre, 12th May 2015, http://www.unep.org/newscentre/default.aspx?DocumentID=26816&ArticleID=35021, (accessed 23-11-2015).

108 B. Bilitewski, *Waste Manage.*, 2012, **32**, 1; I. Rucevska, C. Nellemann, N. Isarin, W. Yang, N. Liu, K. Yu, S. Sandnæs, K. Olley, H. McCann, L. Devia, L. Bisschop, D. Soesilo, T. Schoolmeester, R. Henriksen and R. Nilsen. *Waste Crime - Waste Risks: Gaps in Meeting the Global Waste Challenge. A UNEP Rapid Response Assessment*, United Nations Environment Programme and GRID-Arendal, *Nairobi and Arendal*, 2015. Available online at http://www.grida.no/publications/rr/waste-crime, (accessed 23-11-2015); K. Geeraerts, A. Illes and J. -P. Schweizer, *Illegal shipment of e-waste from the EU - A case study on illegal e-waste export from the EU to China*, 2015. Available online at http://efface.eu/illegal-shipment-e-waste-eu-case-study-illegal-e-waste-export-eu-china, (accessed 23-11-2015).

109 K. Elo and E. Sundin, *Procedia CIRP*, 2014, **15**, 251.

110 F. Cucchiella, I. D'Adamo, S. C. L. Koh and P. Rosa, *Renewable Sustainable Energy Rev.*, 2015, **51**, 263.

111 S. Kennett, 2degrees Network, 8th December 2013, https://www.2degreesnetwork.com/groups/2degrees-community/resources/worlds-first-automated-recycling-plant-lcd-flat-screen-tvs-set-open, (accessed 23-11-2015).

112 European Commission decision 2009/300/EC of 12 March 2009, *Establishing the revised ecological criteria for the award of the Community Eco-label to televisions*, 2009.

113 F. Ardente, F. Mathieux and M. Recchioni, *Resour. Conserv. Recycl.*, 2014, **92**, 158.

114 Thomson Reuters global television market, http://blog.thomsonreuters.com/index.php/global-television-market-graphic-of-the-day, (accessed 23-11-2015).

115 S. W. Breeden, J. H. Clark, S. J. Cowling, J. W. Goodby and A. S. Matharu, *WO Pat.*, 099352, 2007; X. Zhuang, W. He, G. Li, J. Huang and Y. Ye, *Pol. J. Environ. Stud.*, 2012, **21**, 1921.

116 X. Zeng, F. Wang, X. Sun and J. Li, *ACS Sustainable Chem. Eng.*, 2015, **3**, 1306.

117 D. Nelen, S. Manshoven, J. R. Peeters, P. Vanegas, N. D'Haese and K. Vrancken, *J. Cleaner Prod.*, 2014, **83**, 305.

118 J. -H. Jou, S. Kumar, A. Agrawal, T. -H. Li and S. Sahoo, *J. Mater. Chem. C*, 2015, **3**, 2974.

119 P. Kordt, J. J. M. van der Holst, M. Al Helwi, W. Kowalsky, F. May, A. Badinski, C. Lennartz and D. Andrienko, *Adv. Funct. Mater.*, 2015, **25**, 1955.

120 European Commission critical raw materials, http://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical/index_en.htm, (accessed 23-11-2015).

121 P. Blake, P. D. Brimicombe, R. R. Nair, T. J. Booth, D. Jiang, F. Schedin, L. A. Ponomarenko, S. V. Morozov, H. F. Gleeson, E. W. Hill, A. K. Geim and K. S. Novoselov, *Nano Lett.*, 2008, **8**, 1704; Y. U. Jung, K. -W. Park, S. -T. Hur, S. -W. Choi and S. J. Kang, *Liq. Cryst.*, 2014, **41**, 101.

122 R. Arvidsson, D. Kushnir, S. Molander and B. A. Sandén, *J. Cleaner Prod.*, 2015, DOI: 10.1016/j.jclepro.2015.04.076.

123 J. N. Coleman, *Acc. Chem. Res.*, 2013, **46**, 14.

124 K. Singh and S. Arora, *Crit. Rev. Environ. Sci. Technol.*, 2011, **41**, 807.

125 S. B. Moore and L. W. Ausley, *J. Cleaner Prod.*, 2004, **12**, 585; D. Park, D. S. Lee and S. -R. Lim, *Ind. Eng. Chem. Res.*, 2013, **52**, 2379.

126 A. G. Fane, R. Wang and M. X. Hu, *Angew. Chem. Int. Ed.*, 2015, **54**, 3368; J. Lin, W. Ye, J. Huang, B. Ricard, M. -C. Baltaru, B. Greydanus, S. Balta, J. Shen, M. Vlad, A. Sotto, P. Luis and B. Van der Bruggen, *ACS Sustainable Chem. Eng.*, 2015, **3**, 1993.

127 J. C. Colmenares, P. Lisowskia and D. Łomota, *RSC Adv.*, 2013, **3**, 20186.

128 H. L. Parker, V. L. Budarin, J. H. Clark and A. J. Hunt, *ACS Sustainable Chem. Eng.*, 2013, **1**, 1311.

129 M. Razali, J. F. Kim, M. Attfield, P. M. Budd, E. Drioli, Y. M. Lee and G. Szekely, *Green Chem.*, 2015, **17**, 5196.

130 B. Manu and S. Chaudhari, *Bioresour. Technol.*, 2002, **82**, 225.

131 M. Banchero, *Color. Technol.*, 2012, **129**, 2; E. Bach, E. Clleve and E. Schollmeyer, *Rev. Prog. Color. Relat. Top.*, 2002, **32**, 88.

132 A. J. Hunt, E. H. K. Sin, R. Marriott and J. H. Clark, *ChemSusChem*, 2010, **3**, 306.

133 L. Chen, B. Wang, X. Ruan, J. Chen and Y. Yang, *J. Cleaner Prod.*, 2015, **107**, 550.

134 R. Bianchini, G. Cevasco, C. Chiappe, C. Silvio Pomelli and M. J. R. Douton, *ACS Sustainable Chem. Eng.*, 2015, **3**, 2303.

135 D. Brown, in *Biodegradability of Surfactants*, Es: D. R. Karsa and M. R. Porter, Spring Science+Business Media, Dordrecht, 1995, pp. 1-18.

136 M. J. Scott and M. N. Jones, *Biochim. Biophys. Acta Biomembr.*, 2000, **1508**, 235.

137 J. H. P. Tyman and I. E. Bruce, *J. Surfactants Deterg.*, 2004, **7**, 169.

138 P. Foley, A. Kermanshahi Pour, E. S. Beach and J. B. Zimmerman, *Chem. Soc. Rev.*, 2012, **41**, 1499; K. S. Arias, S. I. Al-Resayes, M. J. Climent, A. Corma and S. Iborra, *ChemSusChem*, 2013, **6**, 123; K. S. Arias, M. J. Climent, A. Corma and S. Iborra, *ChemSusChem*, 2014, **7**, 210.

139 Y. Qin, G. Zhang, J. Zhang, Y. Zhao and J. Zhao, *J. Surfactants Deterg*., 2006, **9**, 227.

140 Q. -Q. Zhang, B. -X. Cai, W. -J. Xu, H. -Z. Gang, J. -F. Liu, S. -Z. Yang and B. -Z. Mu, *Sci. Rep.*, 2015, **5**, 9971.

141 P. S. Shuttleworth, J. H. Clark, R. Mantle and N. Stansfield, *Green Chem.*, 2010, **12**, 798.

142 Y. Wang, in *Ecotextiles: The Way Forward for Sustainable Development in Textiles*, Ed. M. Miraftab and A. R. Horrocks, CRC Press, Boca Raton, 2007, p. 26-32.

143 C. Mihut, D. K. Captain, F. Gadala-Maria and M. D. Amiridis, *Polym. Eng. Sci.*, 2001, **41**, 1457; M. J. Realff, J. C. Ammons and D. Newton, *Polym.-Plast. Technol. Eng.*, 1999, **38**, 547.

144 Interface modular carpet tiles, http://interface.com/CA/en-CA/about/modular-carpet-tile/ReEntry-20-en_CA, (accessed 23-11-2015); Switchable adhesives for carpet tiles: a breakthrough in sustainable flooring, http://www.carpetrecyclinguk.com/downloads/5-6JulyPeterShuttleworthSwitchableadhesives.pdf, (accessed 23-11-2015).

145 European Bioplastics bioplastics Market, http://en.european-bioplastics.org/market, (accessed 23-11-2015); French law introduces measures to strengthen bioplastics market, http://en.european-bioplastics.org/blog/2015/07/23/pr-20150723, (accessed 23-11-2015).

146 T. A. Hottle, M. M. Bilec and A. E. Landis, *Polym. Degrad. Stab.*, 2013, **98**, 1898.

147 S. Madival, R. Auras, S. P. Singh and R. Narayan, *J. Cleaner Prod.*, 2009, **17**, 1183.

148 C. R. Álvarez-Chávez, S. Edwards, R. Moure-Eraso and K. Geiser, *J. Cleaner Prod.*, 2012, **23**, 47.

149 British Plastics Federation design products for sustainability, http://bpf.co.uk/sustainable_manufacturing/design/Designing_Sustainability.aspx, (accessed 15-02-2016).

150 V. Siracusa, C. Ingrao, A. L. Giudice, C. Mbohwa and M. D. Rosa, *Food Res. Int.*, 2014, **62**, 151.

151 S. Toniolo, A. Mazzi, M. Niero, F. Zuliani and A. Scipioni, Resour. Conserv. Recycl., 2013, **77**, 61.

152 A. Conte, G. M. Cappelletti, G. M. Nicoletti, C. Russo and M. A. Del Nobile, *Food Res. Int.*, 2015, **78**, 11; H. Williams and F. Wikström, *J. Cleaner Prod.*, 2011, **19**, 43.

153 Natureworks life cycle analysis, http://www.natureworksllc.com/The-Ingeo-Journey/Eco-Profile-and-LCA/Life-Cycle-Analysis, (accessed 23-11-2015).

154 S. -L. Yang, Z. -H. Wu, W. Yang and M. -B. Yang, *Polym. Test.*, 2008, **27**, 957.

155 T. Iwata, *Angew. Chem. Int. Ed.*, 2015, **54**, 3210.

156 Y. Yang, R. Boom, B. Irion, D. -J. van Heerden, P. Kuiper and H. de Wit, *Chem. Eng. Process.*, 2012, **51**, 53.

157 *Poly(lactic acid): Synthesis, Structures, Properties, Processing, and Applications*, Ed. R. A. Auras, L. -T. Lim, S. E. M. Selke and H. Tsuji, John Wiley and Sons, Hoboken, 2010. (a) S. B. Ghosh, S. Bandyopadhyay-Ghosh and M. Sain, p. 305; (b) L. -T. Lim, K. Cink, T. Vanyo, p. 196.

158 J. Pang, M. Zheng, R. Sun, A. Wang, X. Wang and Tao Zhang, *Green Chem.*, 2016, **18**, 342.

159 G. J. M. Gruter and F. Dautzenberg, *EP Pat.*, 1834950, 2007; G. J. M. Gruter and F. Dautzenberg, *EP Pat.*, 1834951, 2007.

160 S. K. Burgess, R. M. Kriegel and W. J. Koros, *Macromolecules*, 2015, **48**, 2184.

161 L. McTigue-Pierce, Packaging Digest, 25th July 2014, http://www.packagingdigest.com/resins/pef-will-not-oust-pet-for-beverage-bottles-anytime-soon140724, (accessed 23-11-2015).

162 J. Hall and H. Vredenburg, *MIT Sloan Management Review*, 2003, **45**, 61.

163 P. Coszach, J. -C. Bogaert and J. Willocq, *US Pat.*, 0142958, 2012; K. Hirao, Y. Shimamoto, Y. Nakatsuchi and H. Ohara, *Polym. Degrad. Stab.*, 2010, **95**, 86.

164 W. Kaminsky and F. Hartmann, *Angew. Chem. Int. Ed.*, 2000, **39**, 331; A. Pifer and A. Sen, *Angew. Chem. Int. Ed.*, 1998, **37**, 3306.

165 A. A. Garforth, S. Ali, J. Hernández-Martínez and A. Akah, *Curr. Opin. Solid State Mater. Sci.*, 2004, **8**, 419.

166 P. Coszach, J. -C. Bogaert and J. Willocq, *US Pat.*, 8431683, 2013; T. M. Ford and J. V. Hockessin, *US Pat.*, 5342969, 1994; L. D. Brake, *US Pat.*, 5264617, 1993.

167 C. S. M. Pereira, V. M. T. M. Silva and A. E. Rodrigues, *Green Chem.*, 2011, **13**, 2658; D. Prat, A. Wells, J. Hayler, H. Sneddon, C. R. McElroy, S. Abou-Shehada and P. J. Dunn, *Green Chem.*, 2015, **18**, 288.

168 Y. Kikuchi, M. Hirao, H. Sugiyama, S. Papadokonstantakis, K. Hungerbühler, T. Ookubo and A. Sasaki, *Int. J. Life Cycle Assess.*, 2014, **19**, 307; W. Kaminsky, M. Predel and A. Sadiki, *Polym. Degrad. Stab.*, 2004, **85**, 1045.

169 M. Goto, *J. Supercrit. Fluids*, 2009, **47**, 500.

170 W. Haas, F. Krausmann, D. Wiedenhofer and M. Heinz, *J. Ind. Ecol.*, 2015, **19**, 765.

171 E. P. A. van Bruggen, PhD thesis, Delft University of Technology, 2015. Available online at http://repository.tudelft.nl/view/ir/uuid:eb01f234-3098-4b2a-bb24-700a22e70652, (accessed 24-11-2015).

172 I. A. Ignatyev, W. Thielemans and B. van der Beke, *ChemSusChem*, 2014, **7**, 1579.

173 European Commission waste framework directive end-of-waste criteria, http://ec.europa.eu/environment/waste/framework/end_of_waste.htm, (accessed 24-11-2015).

174 Towards the circular economy: accelerating the scale-up across global supply chains, http://www.ellenmacarthurfoundation.org/assets/downloads/publications/Towards-the-circular-economy-volume-3.pdf, (accessed 24-11-2015).

175 A. P. Abbott, A. D. Ballantyne, J. P. Conde, K. S. Ryder and W. R. Wise, *Green Chem.*, 2012, **14**, 1302.

176 G. Kale, T. Kijchavengkul, R. Auras, M. Rubino, S. E. Selke and S. P. Singh, *Macromol. Biosci.*, 2007, **7**, 255.

177 J. I. García, E. Pires, L. Aldea, L. Lomba, E. Perales and B. Giner, *Green Chem.*, 2015, **17**, 4326; K. M. Docherty, S. Z. Hebbeler and C. F. Kulpa Jr., *Green Chem.*, 2006, **8**, 560.

178 ASTM standard D6866, *Standard Test Methods for Determining the Biobased Content of Solid, Liquid, and Gaseous Samples Using Radiocarbon Analysis*, DOI: 10.1520/D6866-12; TÜV Rheinland DIN CERTCO certification scheme for bio-based products, http://www.dincertco.de/en/dincertco/produkte_leistungen/zertifizierung_produkte/umwelt_1/biobasierte_produkte/biobasierte_produkte_mehr_nachhaltigkeit.html, (accessed 23-11-2015); Vinçotte OK biobased certification scheme, http://www.okcompost.be/en/recognising-ok-environment-logos/ok-biobased, (accessed 23-11-2015).

179 International Sustainability and Carbon Certification ISCC Plus, http://www.iscc-system.org/en/iscc-system/iscc-plus, (accessed 23-11-2015).

180 Cradle to Cradle certified standards and guidance, http://www.c2ccertified.org/resources/collection-page/cradle-to-cradle-certified-resources, (accessed 23-11-2015).

181 Forum for the Future design for demand tool, https://www.forumforthefuture.org/project/design-demand/overview, (accessed 15-02-2016); Forum for the Future the circular economy business model toolkit, https://www.forumforthefuture.org/project/circular-economy-business-model-toolkit/overview, (accessed 15-02-2016).

182 Y. Zhang, H. Zheng, B. Chen, M. Su and G. Liu, *Front. Earth Sci.*, 2015, **9**, 91; P. Desrochers, *J. Cleaner Prod.*, 2004, **12**, 1099.

183 E. A. Quadrelli, G. Centi, J. -L. Duplan and S. Perathoner, *ChemSusChem*, 2011, **4**, 1194; G. Centi, G. Iaquaniello and S. Perathoner, *ChemSusChem*, 2011, **4**, 1265; S. Perathoner and G. Centi, *ChemSusChem*, 2014, **7**, 1274; A. Scott, *Chem. Eng. News*, 2015, **93**, 10.

184 F. S. Pereira, L. J. Pereira, D. F. A. Crédito, L. H. V. Girão, A. H. S. Idehara and E. R. P. González, *RSC Adv.*, 2015, **5**, 81515; J. H. Clark, E. M. Fitzpatrick, D. J. Macquarrie, L. A. Pfaltzgraff and J. Sherwood, *Catal. Today*, 2012, **190**, 144.

185 W. Bajdur, J. Pająjczkowska, B. Makarucha, A. Sułkowska and W. W. Sułkowski, *Eur. Polym. J.*, 2002, **38**, 299; C. Zhuo and Y. A. Levendis, *J. Appl. Polym. Sci.*, 2014, **131**, 39931; J. R. Dodson, E. C. Cooper, A. J. Hunt, A. Matharu, J. Cole, A. Minihan, J. H. Clark and D. J. Macquarrie, *Green Chem.*, 2013, **15**, 1203.

186 Finnish Forest Industries paper and pulp industries, https://www.forestindustries.fi/industry/paper_cardboard_converted/paper_pulp (accessed 23-11-2015).

187 S. Van den Bosch, W. Schutyser, R. Vanholme, T. Driessen, S. -F. Koelewijn, T. Renders, B. De Meester, W. J. J. Huijgen, W. Dehaen, C. M. Courtin, B. Lagrain, W. Boerjan and B. F. Sels, *Energy Environ. Sci.*, 2015, **8**, 1748; G. Faulkner, Recycling and Waste World, 8th June 2015, http://www.recyclingwasteworld.co.uk/news/belgian-scientists-find-way-to-turn-paper-industry-waste-into-chemicals/86014, (accessed 23-11-2015).

188 F. Cao, T. J. Schwartz, D. J. McClelland, S. H. Krishna, J. A. Dumesic and G. W. Huber, *Energy Environ. Sci.*, 2015, **8**, 1808; J. Sherwood, M. De bruyn, A. Constantinou, L. Moity, C. R. McElroy, T. J. Farmer, T. Duncan, W. Raverty, A. J. Hunt and J. H. Clark, *Chem. Commun.*, 2014, **50**, 9650; G. G. Gerosa, R. A. Spanevello, A. G. Suárez and A. M. Sarotti, *J. Org. Chem.*, 2015, **80**, 7626.

189 J. M. Holderby and W. A. Moggio, *J. Water Pollut. Control Fed.*, 1960, **32**, 171.

190 D. Queirós, S. Rossetti and L. S. Serafim, *Bioresour. Technol.*, 2014, **157**, 197.

191 Confederation of European Paper Industries ERPC monitoring report 2014, http://www.cepi.org/node/19706, (accessed 23-11-2015).

192 M. Delgado-Aguilar, Q. Tarrés, M. À. Pèlach, P. Mutjé and P. Fullana-i-Palmer, *Environ. Sci. Technol.*, 2015, **49**, 12206; A. Villanueva and H. Wenzel, *Waste Manage.*, 2007, **27**, S29.

193 R. de Man and H. Friege, *Waste Manage. Res.*, 2016, **34**, 93; Anti-climactic release of revised circular economy package - the loop stays open, http://ecostandard.org/?p=2616, (accessed 15-02-2016); J. Lambert and D. Skrlec, EurActiv, 4th December 2015, http://www.euractiv.com/sections/sustainable-dev/circular-economy-package-waste-job-opportunities-320134, (accessed 15-02-2016); B. Messenger, Waste Management World, 10th December 2015, http://waste-management-world.com/a/zero-waste-europe-blasts-circular-economy-package-as-too-weak, (accessed 15-02-2016); J. Eagle, Food Production Daily, 11th December 2015, http://www.foodproductiondaily.com/Packaging/Debate-rages-on-over-revised-Circular-Economy-Package, (accessed 15-02-2016).

194 K. Hobson, *Prog. Hum. Geogr.*, 2016, **40**, 88; D. A. R. George, B. C. -A. Lin and Y. Chen, *Environmental Modelling & Software*, 2015, **73**, 60; P. Ghisellini, C. Cialani and S. Ulgiati, *J. Cleaner Prod.*, 2016, **114**, 11; M. S. Andersen, *Sustain. Sci.*, 2007, **2**, 133.

195 G. M. Whitesides, *Angew. Chem. Int. Ed.*, 2015, **54**, 3196.