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Current approaches to waste polymer utilization and minimization: a review

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Abstract

The mass production of polymer products, in particular plastics, and their widespread use depending on the inherent advantages they have, make these materials ironically a threat to life on Earth. Polymer recycling is being considered as one of the most widely accepted remedies to the threat of growing amounts of plastic waste by both the public and scientists. In practice, recycling is associated with many difficulties, such as problems related to separation, sorting and cleaning operations, lack of fiscal subsidies, instability of selective garbage separation programs, high transport and electricity costs, etc. Still, a large section of society and the authorities agree on the necessity and importance of recycling to protect the environment, and natural habitats and resources for future generations in a balanced manner to conserve raw materials, and to reduce energy consumption, municipal solid waste production and greenhouse gas emission. The recycling effort is almost endless in itself and includes a variety of approaches such as refurbishing, mechanically reshaping, chemically treating, thermally utilizing, etc. Some novel approaches such as application in carbon capture or synthesis of carbon nanostructures from the plastic waste are among the new process technologies of recycling. From traditional and promising polymer waste utilization approaches, this review will highlight sustainable methods to reduce impacts of plastic waste on the environment.

Keywords: environmental remediation|; process technology; recycling; sustainable processing; waste treatment; waste minimisation

INTRODUCTION

Polymers and plastics are seen in many areas of everyday life from household items to industrial products. A polymer is a large molecule, or a macromolecule, built up from many repeated subunits known as monomers. The term 'plastic' is originated from the Greek word 'plastikos', meaning 'moldable'. Plastics are classified as thermoplastics and thermosets. Thermoplastics can be heated and shaped several times with deterioration in the physical and mechanical properties while thermosets are produced via a setting reaction which gives them their permanent shape. The key difference between plastics and polymers is that all plastics are polymers but not all polymers are plastics. A polymer can either be biological or synthetic, while plastics are made from petroleum and its derivatives.

Both synthetic, e.g. poly(ethylene terephthalate) (PET), polyethylene (PE), polypropylene (PP), and natural, e.g. cellulose, starch, chitin, polymers play essential and ubiquitous roles in everyday life. The backbone chains of addition polymers, e.g. polyolefins such as PE, PP, polystyrene (PS) and poly(vinyl chloride) (PVC), are solely built of carbon atoms and quite resistant to degradation or hydrolytic cleavage. Consequently, these polymers are considered non-biodegradable.[1] The condensation polymers, on the other hand, contain heteroatoms such as O and N on their backbones. Polyamides (or nylons), polyesters (i.e. PET and polycarbonate (PC)) and polyurethanes are some examples of this class. These polymers are potentially susceptible to degradation by the hydrolytic cleavage due to hydrophilic amide or ester linkage between monomers. However, when they are disposed to landfills, condensation polymers as well will persist for at least decades, and probably for centuries.[2] This is mainly because commercial products resist oxidation and biodegradation due to the additives they have, such as anti-oxidants and stabilizers. Moreover, their molecular weights are usually too high. It is reported that biodegradation begins only for molecular weight values of a few tens of thousands, which can be considered very low for many commercial polymers.[3,4] Crystallinity is another parameter that adversely affects biodegradation.[5] For the polymers listed in the first group, i.e. those synthesized by addition polymerization, degradation by natural means is even more difficult because of their chemically inert character.

Commercial plastics are made up of polymers and additives such as plasticizers, stabilizers, antioxidants, impact modifiers, reinforcing agents or fillers, pigments, compatibilizers, lubricants, flame retardants, and so on. These chemicals are added to give the polymer enhanced functionality; without the presence of additives, many polymeric materials would be of limited use. Unfortunately, concerns also exist over the additives; e.g. phthalates or bisphenol A. These chemicals are reported to be harmful to human health through some biological mechanisms.[6] The polymer content in a plastic can vary widely from less than 20% to

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nearly 100%.[7] The diversity in plastic formulations complicates recycling activities. In order to recover most of the inherent value of the pristine plastic and to produce a new product with properties mimicking those of the virgin material, the waste plastic to be recycled must have a uniform and well-defined composition. This makes separation, sorting and cleaning (for instance, separation of PET bottles from other plastic bottles, sorting them according to colors, and removal of non-PET components such as label, label adhesives, and cap) the central parts of a plastic recycling process.

The global production of plastics, excluding fibers of PET, PP, and polyamide, was approximately 322 million tons in 2015 and 335 million tons in 2016.[8] Around 50% of plastics are made for single-use applications, such as disposable consumer items and packaging; the rest is used for long-term infrastructures such as pipes and structural materials and for durable consumer applications with intermediate lifespan such as in furniture and vehicles in almost equal amounts.[9] It is estimated that the amount of plastic waste entering the ocean from land was between 4.8 and 12.7 million tons globally in 2010.[10] Plastic wastes, therefore, form a major component of marine litter, affecting the aquatic and the mainland life negatively.

A recently published report by the Danish Environmental Protection Agency concluded that plastic grocery bags made of low-density PE (LDPE) are more environmentally friendly than paper, bio-plastic and cotton alternatives.[11] The study shows that a paper bag would need to be used 43 times to achieve the same per-use resource expenditure as an LDPE-bag. Greater energy requirement for its production means more carbon emissions. In order to assure the environmental impact is similar to the LDPE-bag, a bio-material based plastic needs to be recycled 42 times, while a cotton-bag has to be reused up to 7100 times (and around 20 000 times, if the cotton is organic). In 2015, England stopped handing out plastic bags for free, and instead charged five pence per LDPE-bag.[12] This resulted in almost a six billion reduction in the number of plastic bags handed out in 6 months.[13] In 2016, France banned plastic plates, cups, and utensils with a law that will go into effect in 2020, becoming the first country in the world to do so. Exceptions will be allowed for items made of compostable, bio-sourced materials.[14] In 2018, Seattle became the first major US city to fully ban single-use utensils and straws in food service.[15,16] There will be a net benefit of discarding less single-use plastic materials, however, there are serious concerns about their replacements. Recycling plastic materials seems eco-friendlier than replacement of plastic with paper, bio-plastic or, in particular, cotton.

In many previous publications, conventional recycling technologies such as pyrolysis and depolymerization, and recycling paths of various polymers, e.g. PET and PE, or polymer classes, e.g. polyurethanes, polyamides and bioplastics, have been reviewed in detail.[17–24] In this review, we have dealt with traditional and promising recycling technologies in general, without specifically focusing on a certain polymer or method. We have emphasized the importance and necessity of the development of new process technologies for polymer waste utilization in order to make a positive impact on the world we live in. This review also presents some applications and, finally, suggestions on measures that can be taken on a wide scale, from end-users to manufacturers, to make recycling/utilization as widely applicable as possible.

PLASTIC WASTE MANAGEMENT: CURRENT STATE AND CONVENTIONAL METHODS OF RECYCLING

Recycling is the process of using recovered material to manufacture a new product or to recover energy once material enters the waste stream. Energy recovery, where the high-yielding calorific value of polymer is utilized by controlled combustion as a fuel, presents lower environmental performance than material recovery as it does not reduce the demand for new material and may cause emissions and fly and bottom ash containing toxic residues such as lead and cadmium.[25] Incineration has been widely assessed as ecologically unacceptable in the last decade as many environmental regulations have been implemented for a more sustainable recycling-oriented society.[26] In the order of decreasing environmental desirability, the main strategies for management of plastic waste can be specified as reduce, reuse, recycle (materials) and recover (energy). Landfilling is considered the least desirable management strategy and should be limited to the necessary minimum.[9] Yet, landfilling has also been regulated, e.g. by the European Commission with the Council Directive 99/31/EC to reduce the negative effects of landfilling on water, air and soil sources. Beyond the concerns related to collection, transportation and long-term risks of soil and groundwater contamination by toxic additives, a major drawback of landfilling arises from a sustainability aspect; that is none of the materials used to produce the plastic is recovered, the material flow is linear rather than cyclic.[9]

Among countries in the European Union, waste management strategies vary significantly as can be seen in Fig. 1.[27] Germany, the Netherlands, Belgium, and Austria recycle more than half of their waste. Almost all of the remaining waste is combusted to recover energy in these countries. In Luxemburg and France too, incineration ranks second in waste management schemes after material recycling. In Sweden and Denmark landfilling rates are less than 5%. However, for the rest of the European Union countries the least desirable management option, landfilling, is the most applied method. Especially in Croatia, Malta, Bulgaria, and Romania, more than 90% of waste ends up in landfills.

The terminology used for plastic recycling is actually complex and sometimes confusing. According to American Society for Testing and Materials (ASTM) D5033 definitions recycling includes four categories: primary (mechanical reprocessing of scrap materials with controlled history into products with equivalent properties), secondary (mechanical reprocessing of used materials into products requiring lower properties), tertiary (recovery of valuable chemical constituents such as monomers or additives) and quaternary (recovery of energy) as presented in Scheme 1.[9,28,29] The'transformation'of waste to more useful products or materials is called valorization. The 'transformation' may include any process by which the waste can be transformed into valuable products via reutilization or recycling. The term 'valorizing' means producing an energy source. Therefore, the tertiary and quaternary categories fall into valorizing, while primary recycling covers reuse of an object.

Primary recycling

Primary recycling refers to recovery and reuse of materials without being changed and usually for the very same purpose.[30] It ensures simplicity and low cost, however, deals only with the recycling of clean, uncontaminated and single-type waste. Only certain plastics are recycled in this manner due to purity requirements, and there is also an obvious limit on the number of cycles for each material.[31]

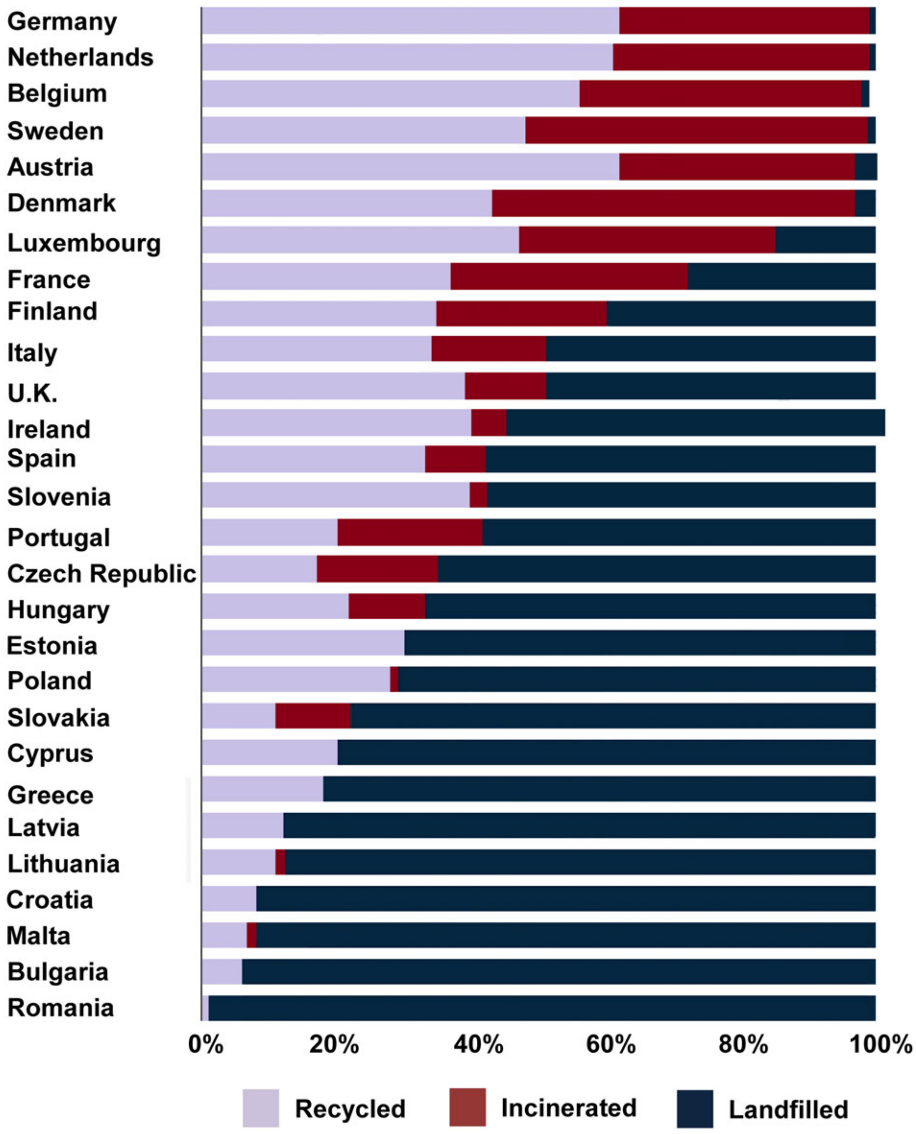


Figure 1. Recycling rates in Europe in 2011.[27]

Producing a new bottle from a scrap bottle is an example of this recycling category.

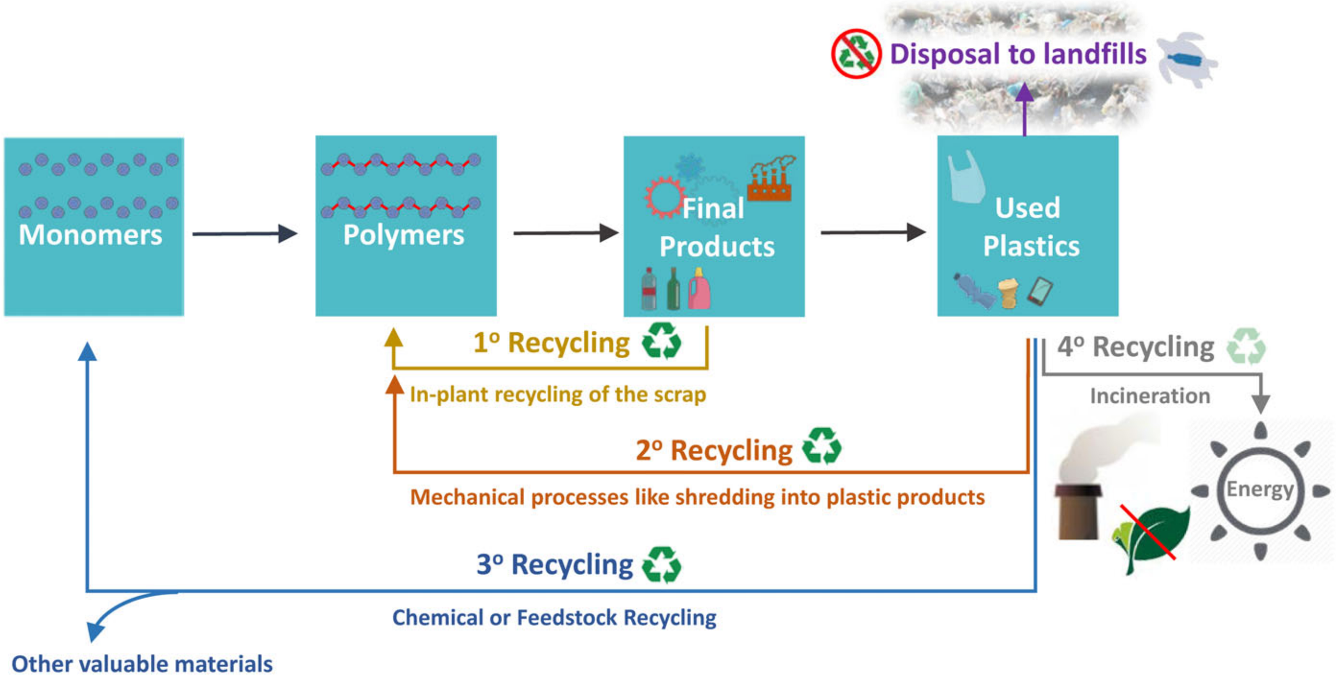
Secondary recycling (mechanical recycling)

Mechanical or secondary recycling refers to reprocessing of waste plastics by physical means. The polymeric waste is generally reprocessed into granules by conventional extrusion after being separated from its associated contaminants. Collection/segregation, cleaning, and drying, chipping/sizing, coloring/agglomeration, pelletization/extrusion are the steps involved in this approach before the manufacturing of the end product. The main drawback of this method is deterioration of the properties of the product, mainly attributed to decrease in molecular weight after each cycle as a result of chain-scissions.[32] There are other limitations to the mechanical recycling process; temperature-sensitive plastics, composites, polymeric blends and plastics that do not flow at elevated temperatures such as thermosets and polymers with high melt viscosities, e.g. fluoropolymers, cannot be processed mechanically. Practically, only poly(ethylene terephthalate) (PET) and polyethylenes (HDPE, LDPE, LLDPE) are recycled by a mechanical process. All other plastic wastes are either not recovered or their recovery rate is less than 1% with regard to their total production.[33]

Tertiary recycling (chemical or feedstock recycling)

Chemical or feedstock recycling (tertiary recycling) is defined as the process leading to the decomposition of plastics to their building blocks, i.e. monomers, or other valuable low molecular weight fragments. The monomers obtained can subsequently be re-polymerized to synthesize the original polymer.[34] Partial de-polymerization to oligomers or mixtures of other hydrocarbon compounds are also valuable; these materials may be used as a feedstock or as an input for the production of new plastics and petrochemicals by means of heat or chemical agents.[32] Tertiary recycling is attracting much attention because it is very profitable and beneficial from the sustainability point of view: it reduces the demand for energy and feedstock and the material flow is cyclic.

Pyrolysis or thermal cracking is considered as one of the most promising processes of tertiary recycling, conducted at high temperature and in the absence of oxygen (usually in a nitrogen



Scheme 1. Types of plastic waste recycling.

atmosphere).[35] During the thermal decomposition of polymers, depending on polymer type, chain scissions occur either randomly, yielding low molecular weight fractions, or form the chain-ends, yielding monomers. The decomposition products in the form of liquid oil, char or gases are all valuable as fuel or as feedstock for the production of the same or different plastic materials. If the tertiary recycling process yields energetic products consisting of high contents of carbon and hydrogen atoms with minor or no heteroatom contribution, they become valuable especially for the production of fuels such as automotive gasoline, jet fuel, and diesel products, provided that the products meet a number of strict standards.[36–41] Pyrolysis is conducted with or without a catalyst. Lower temperatures applied during the catalytic process yield faster degradation and a narrower fractional composition of the products. However, the main issue is economic efficiency; commercial catalysts are generally expensive and typically cannot be regenerated.[42–44]

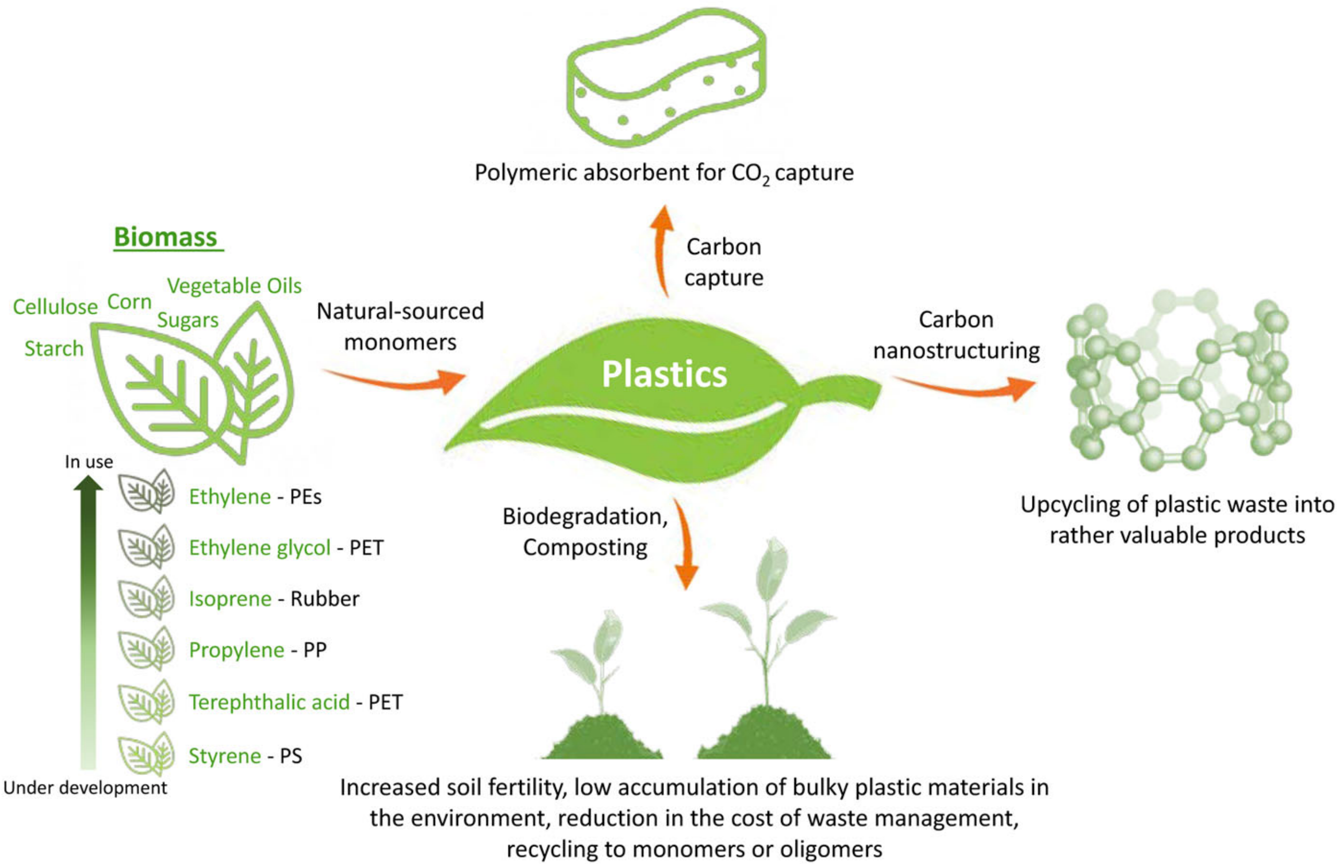
There are various methods for chemical recycling. For polymers synthesized via an *addition polymerization* process, such as polyolefins (PE, PP, PS, PVC, polybutadiene, polyisoprene, etc.), acrylics (polymethacrylates, polyacrylamide polyacrylonitrile, etc.) and other vinyl types (poly(vinyl acetate), poly(vinyl acetals), poly(vinyl ethers), etc.) gasification, pyrolysis, liquid–gas hydrogenation and steam or catalytic cracking are the main subcategories of chemical recycling. The products yielded in chemical recycling of polyolefins contains numerous energetic components, hence they are especially valuable as potential fuels.

For *condensation polymers* such as polyesters (PET, poly(butylene terephthalate), polycarbonates, etc.), polyamides (aliphatic and aromatic nylons, polyimides), formaldehyde resins (phenol–formaldehyde resins, urea–formaldehyde resins, etc.), polyurethanes (polyurethane rubbers and foams, spandex fibers, etc.) and ether polymers (epoxy resins, etc.), the main subcategories of chemical recycling are hydrolysis (acidic, alkaline, and neutral), glycolysis, methanolysis, aminolysis, ammonolysis, and so on. Recycling of condensation polymers such as PET and Nylon by these methods yields monomer units (de-polymerization or monomer recycling) in a relatively short time.[32]

Other chemical recycling methods involves photodegradation,[45–47] ultrasound degradation,[48–53] degradation in microwave reactor,[54–59] etc. Despite all its advantages, unfortunately, chemical recycling is not a widespread method, mainly because of energy costs.[33] Numerous methods of chemical recycling to obtain valuable chemicals such as monomers, petrochemicals or additives from the used polymeric materials are under investigation presently, and sustainable conditions for these processes are under extensive research.

Quaternary recycling (energy recovery)

Recycling of plastic wastes via primary or secondary methods leads to deterioration of the properties. Therefore, continuous recycling could yield substandard and low-quality products. Chemical recycling, on the other hand, is not applied to each polymer because it is not efficient enough or economically sustainable. The end of life of plastics must be analyzed carefully because it eventually becomes economically unprofitable to recycle them further. As it is not reasonable to landfill polymeric wastes both from the environmental and economical points of view, it is beneficial to use the excellent physical properties of plastics in various applications. For instance, the mechanical properties of plastics are utilized in road,[60] pavement[61] or asphalt[62] constructions as modifier or reinforcing filler. Another physical property of plastics, their high calorific value, is quite valuable too; energy recovered from plastic waste can make a major contribution to energy supply. Quaternary recycling refers to the recovery of energy content of plastics by incineration. This is currently the most effective way to reduce the volume of organic materials. However, this method yields considerable toxic substances both in smoke and in ashes and is regarded as ecologically unacceptable.[63]



Scheme 2. Promising and eco-friendly plastic management approaches.

Other valorizing options

The recycling process is divided into four parts, where primary recycling is the use of pre-consumer industrial scrap and salvage, secondary recycling is physical reprocessing, tertiary recycling is chemical processing and quaternary recycling refers to the recovery of energy.[64,65] In this section, a number of new approaches for the utilization of waste plastics were summarized.

Ravichandran *et al.* synthesized and characterized new polyphenolic flame-retardant material from a biodegradable and renewable starting material, cardinal, which is a by-product of cashew nut processing. Polymerization of cardanol took place in aqueous media with different types of oxidants. Promising results were obtained from preliminary studies, indicating that new types of flame retardant materials from bio-based phenols is possible.[66] Hollow spherical sludge carbons were prepared by Wu *et al.* from polystyrene foam sphere and sludge pyrolysis, which was then employed as an adsorbent to treat wastewater.[67] Conversion of waste expanded polystyrene into polymeric azo dyes with sulphonamide group was accomplished by Liu *et al.* through chlorosulfonation, amidation, hydrolysis, diazotization and coupling reactions.[68] Liao *et al.* reported the preparation of doped carbon catalyst for the reduction of oxygen employing precursors; polystyrene foam, melamine and iron chloride.[69] Using a simple technique, Fonseca *et al.* transformed waste polystyrene cups into negative electrode materials to be used in sodium ion batteries.[70]

There exist various materials used to reinforce asphalt. Lately, protecting the environment has become a crucial issue all around the world. Accordingly, carbon fibers and recycled waste packaging polymers seem to be good modifier candidates. For modification of ordinary paving asphalt, Zhang *et al.* preferred waste packaging polyethylene and polyacrylonitrile-based carbon fibers over ordinary polymer modifiers.[71] Because of increasing environmental concerns over the last couple of decades, recycling and benefiting from non-biodegradable elastomeric wastes have become major issues for researchers. In recent years, continuous utilization of waste tires has been well studied.[72–74] Jeong *et al.* reported the preparation of a composite with supercritical carbon dioxide by mixing low-density polyethylene foaming and waste rubber (ethylene-propylene-diene monomer). For optimization of the process, temperature and pressure variations were studied on the foamed microcell formation. The composite prepared was found to be promising for its further use as a foaming mat for artificial turf.[75]

The environmentally continuous disposal and recycling of an increasing amount of electronic wastes have become a waste management matter globally. The disposal of electronic wastes is one of the major environmental challenges. The central components of many electronic devices and printed circuit boards (PCB) may contain various compositions. Serious amounts of toxic components are involved in these PCBs from TVs, laptops, mobile phones etc. together with polymers, ceramics and metals.[76–78] A novel study on the simultaneous use of automotive and electronic rubber waste as fillers in PP composites was reported by Kumar *et al.* This new environmentally friendly approach may enable benefiting from remarkable amounts of polymeric automotive and electronic wastes to fabricate high-value polymer compositions.[76]

Polymeric adsorbents can be employed for heavy metal adsorption since they can be regenerated easily and they have good mechanical properties compared to other adsorbents like silica gel, cellulose and activated carbon.[79] Alsewailem and Aljlil studied cost-efficient adsorbents to remove lead from wastewater using discarded post-consumer polystyrene which was obtained cost-free. Results obtained from adsorption isotherms showed that recycled polymer compositions were a rather powerful tool compared with virgin polymer composites.[80]

PROMISING APPROACHES

Current plastic waste utilization techniques are not applied at large scale. Mechanical or secondary recycling is the only widely applied approach, and unfortunately it is not being used for the treatment of thermoplastics beyond polyethylenes and PET, which represent 37% and 9% of the annual plastic produced, respectively. There is a need now more than ever to develop new recycling technologies which reduce energy consumption, increase the amount or value of products and reduce or completely eliminate toxic waste in a sustainable, economically feasible and socially responsible manner. Some eco-friendly options, summarized in Scheme 2, look promising to help the management of polymers in a sustainable way. These options are reviewed in detail below.

Carbon capture using waste plastic sources

Carbon dioxide (CO_2) emitted as a result of combustion of fossil fuels is among the main causes of global warming and climate change.[81] The capture and storage of CO_2 generated during combustion at coal- or gas-burning power plants is attractive for reducing CO_2 emissions into the atmosphere.[82] There exist economic and technical procedures that need to be followed for solid adsorbents employed in pre- and post-combustion CO_2 capture. The adsorbent should engage in a gas stream and leave the water–gas shift reactor at a temperature of approximately 40°C and a total pressure of around 30–45 bar. The major component here is the gas-shifter fuel, that is H_2, for which the amount should be greater than 60 mol%. The temperature and pressure of the gas stream cause pressure-swing cycles to be principally attractive.[83] A preferred adsorbent should have good selectivity towards CO_2 to be able to specifically adsorb it among other components in the gas stream, have large sorption capacity in order to be considered as an economically appropriate process and have good physicochemical stability which includes steadiness against moisture, heat and acidic gases like hydrogen sulphide. The candidate materials for CO_2 capture and storage should also be cost-effective and their synthesis should be scalable.[84] Combination of high porosity and good chemical stability can be found in microporous organic polymers.[85] The scale-up costs are usually the prime concern in the production of porous polymer adsorbents synthesized using precious metals and catalysts, which is the case in conjugated microporous polymers.[86] Sneddon *et al.* reported the synthesis of a high-surface-area composite material using amine-functionalized waste PVC as the source material for the first time for CO_2 adsorption (Fig. 2). The synthesis scheme was based on a simple one-step reaction, which allowed it to be scalable for the further development of industrial CO_2 capture and storage units. Moreover, compared with un-functionalized mesoporous substrates, aminated PVC adsorbent was found to have exceptional hydrophobic characteristics which enable it to be used in elevated moisture content flue gases.[87]

In Europe, recovery of 69.2% of post-consumer plastics was accomplished via energy recovery processes and recycling, whereas the disposal of the rest, 30.8%, took place together with the municipal solid wastes in landfills which in return reduced the landfill capacity as a result of low solid waste density, in 2014.[88] Fu *et al.* reported a technique for the synthesis of hyper crosslinked polymers using Friedel-Crafts reaction employing waste-expanded polystyrene foam as raw material and 1,2-dichloroethane as both solvent and crosslinker. With this approach, it was made possible to synthesize cost-effective hyper crosslinked polymers in a fast and facile manner. Additionally, it was found that BET surface area of the polymers could be controlled by tuning the reaction time and the weight ratio between polystyrene foam and catalyst.[89] The hyper crosslinked polymers synthesized showed better adsorption capacities compared to other CO_2 capturing materials and were found to be cost-efficient for production at industrial scales. A schematic representation of the synthesis process can be seen in Fig. 2.

Because amine functionality boosts the CO_2 adsorption capacity, cost-efficient supports were advanced on these terms in order to cope with the current amine scrubbing system limitations. Most of the effort has been put into exploring an appropriate candidate with effective features to meet the energy criteria, however, their economical perspective restrain their feasible application.[90,91]

Synthesis of carbon microspheres and nanotubes from plastic wastes

Upcycling refers to the conversion of a waste material into a valuable product. It is a sustainable concept and prevents waste being directly thrown into landfill or an incinerator. It also is quite useful since it makes use of inexpensive materials. It is commonly true that the more innovative the transformation of an upcycle entity, the more vendible it is. Therefore, upcycling is a constructive method due to cost benefits and waste reduction.

Pol claimed that waste plastics can be completely converted into high-purity carbon microspheres that would be crucial industrially.[92] Carbon microspheres are promising tools for various applications such as in printers, batteries, toners, paints and tires. Yang *et al.* reported the synthesis of amorphous carbon nanospheres with sizes ranging between 140 and 200 nm through treatment of poly(tetrafluoroethylene) (PTFE) in supercritical water at 550°C with $Ca(OH)_2$ as de-fluorination agent.[93] Zou *et al.* successfully degraded PTFE with a mild and cost-efficient method at low temperature.[94]

Carbon nanotubes (CNTs) can be classified depending on their graphene sheets as single-walled CNTs (SWCNTs) and multi-walled CNTs (MWCNTs) which are continuous cylinders of a graphene sheet with hexagonal units consisting of sp^2-bonded carbon atoms and multiple rolled graphene sheets, respectively. Waste plastics are among the carbon sources through which CNTs can be produced. This way, both the waste problem can be solved and resourceful product can be produced. Plastics pyrolysis is another technique to produce high-value CNTs with bizarre physical and chemical properties. This technique has been employed for some time and follows mixing plastics with catalyst in a single reactor or passing the pyrolysis products of plastic through a second stage catalyst reactor.[95–98] Wu *et al.* reported the production of hydrogen and high-value CNTs from waste plastics, employing a pyrolysis-reforming method consisting of a two-stage reaction system in the presence of steam and Ni-Mn-Al catalyst. The waste plastics comprised commercial waste high-density polyethylene (HDPE), re-granulated HDPE containing PVC and plastics from motor oil containers. The results showed that a

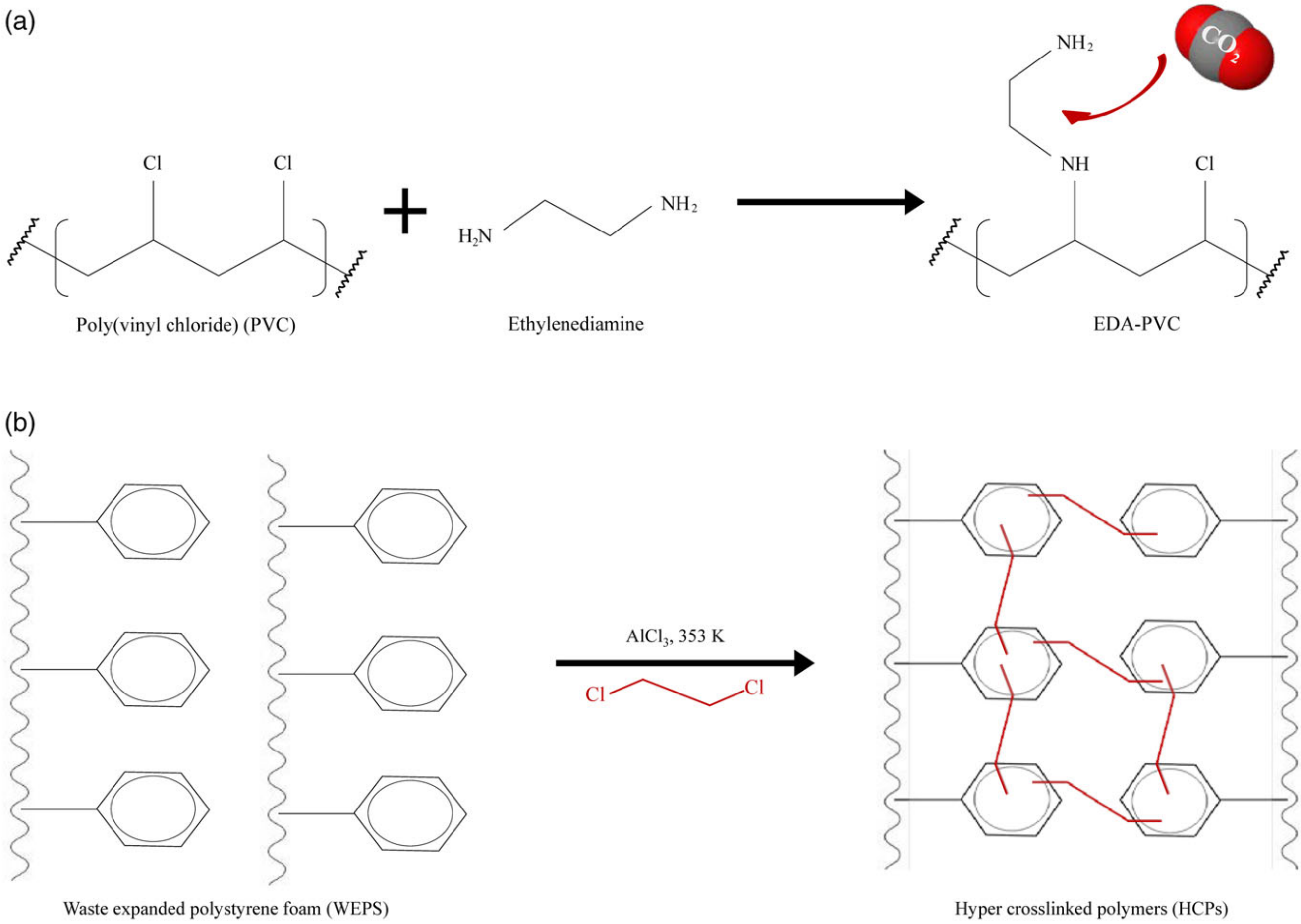
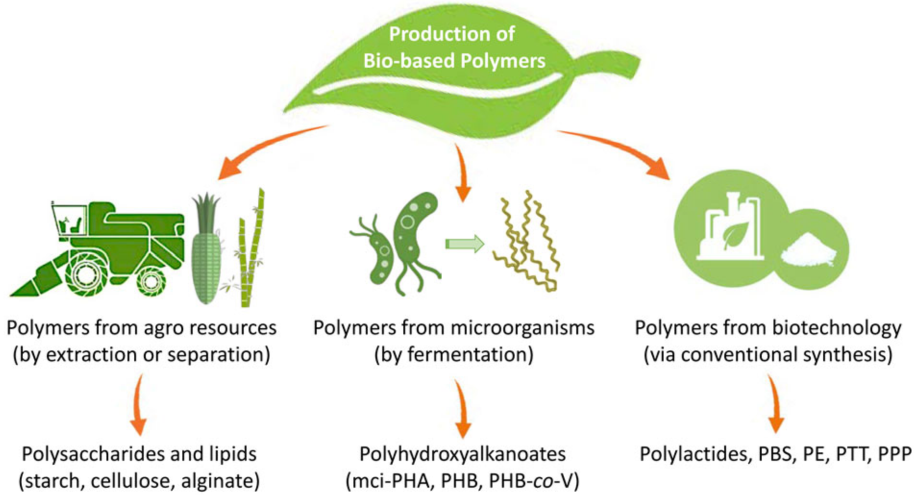


Figure 2. Schematic representation of chemical processes developed by (a) Sneddon *et al.*[87] and (b) Fu *et al.*[89]



Scheme 3. Bio-based polymer manufacturing route.

pyrolysis-reforming process produces hydrogen an in the meantime, CNTs were formed on the catalyst.[99]

Other than waste plastics and hydrocarbon gases, pyrolysis oils can also be employed to produce CNTs. In a study by Quan *et al.*, high phenol-containing pyrolysis oil was obtained, from a printed circuit board. Then, hollow-centered and straight CNTs were produced with the pyrolysis oil.[100] It should be noted that during waste plastic CNT transformation, along with CNT, producing hydrogen is also quite beneficial. For instance, Nahil *et al.* studied a number of Ni-based catalysts for the co-production of CNTs and hydrogen through pyrolysis of waste plastics.[101] Then, in-line catalytic reforming of pyrolysis vapours was performed employing a two-stage reaction system in which the first-stage pyrolysis was performed at 500°C and second-stage catalytic reforming was

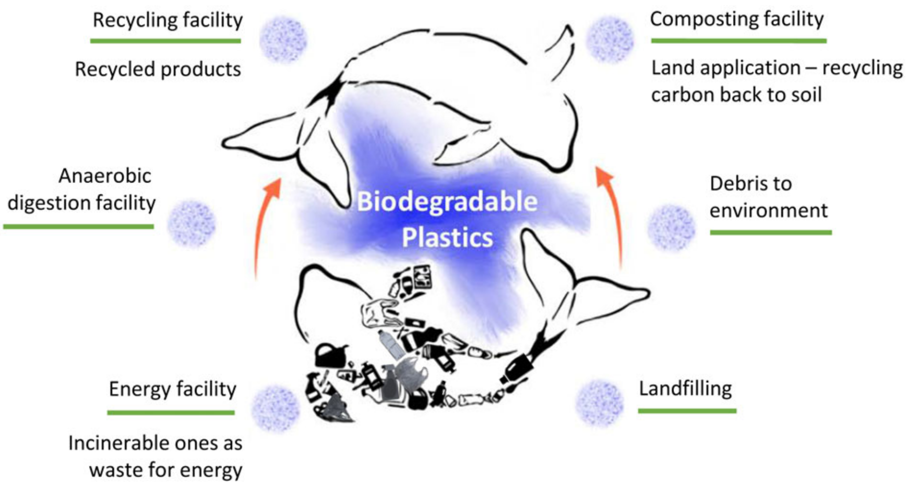
Table 1. Natural-sourced monomers: transformation into commodity plastics

Source	Natural-based monomers	Modification	Application	Reference
Bagasse, corn cobs, oat hulls	Furfural	Conversion to adipic acid and hexamethylene diamine, reaction with phenol	Production of Nylon, 66 and thermosetting phenolics	107,108,111
Rosin	Terpene, levopimaric acid, etc.	Chemical conversion and polymerization	Thermoplastic resins, high temperature resistant resins	107,108,111,118,119
Vegetable oils, e.g. soybean oil, castor oil, rape seed oil, etc.	Fatty acids such as oleic acid, linoleic acid, erucic acid, etc.	Extraction, epoxidation, catalytic reactions, etc.	A large range of polymers from soft rubbers to ductile or rigid plastics, e.g. polyurethanes, polyesters, polyethers, etc.	120–126
Sugar waste	Glucose	To Sorbitol	As Polyol	107,108,111
Molasses	Sucrose	To hydroxymethyl furfural and sucrose methacrylate	Variety of chemicals and polymers	
Carbohydrates	Lactic acid and levulinic acid	Extraction, catalytic reactions, etc. and polymerization	Polylactide copolymers	107,108,111
Rhus fernisifera	Urushiol	Oxidative polymerization	Specialty coatings	107,108,111
Anacardium occidentelle	Cardanol	Chemical modification and polymerization	High performance polymers	107,108,111
Crude cells containing PHA	Microbial synthesized monomers	Pretreatment, extraction, and purification	Poly(hydroxy alkanoates) (PHAs)	127–129
Suberin	Suberin monomers	Crosslinking	Suberin polymers	107,108,111
Sugar	Ethylene	Dehydration of ethanol obtained from sugar into ethylene	Polyethylene	130
Sugar	Propylene	Catalytic conversion of ethanol into propylene	Polypropylene	130
Isopentenyl diphosphate	Isoprene	Biosynthesis using bacterial sources	Polyisoprene	130
Sugars and cellulosic biomass	Ethylene glycol	Hydrolysis, hydrogenolysis, catalytic conversion	Synthesis of PET	131–133
Sugars and cellulosic biomass	Terephthalic acid	Catalytic aerobic oxidation	Synthesis of PET	131
Glucose	Styrene	Microbial biosynthesis	Polystyrene and styrene-based copolymers	134
Biomass, e.g. glucose sources	Succinic acid	Extraction, fermentation	Polyamides, polyesters, poly(ester amide)s	135–137
Polysaccharides such as starch, cellulose	Isosorbide, isomannide and isoidide	Depolymerization, hydrogenation, dehydration	Polyesters, polycarbonates, polyethers and polyurethanes	138–140
Lignin	Vanillin, vanillic acid, terephthalic acid	Extraction, derivations	Polyurethanes, PET, various aromatic polymers	141–145

carried out at 800°C. They also revealed that addition of Mn into Ni-Al catalyst dramatically increased the CNT production and the hydrogen yield was also found to be high. The suggestion was that the weak interaction between metal particles and catalyst support had a significant role in CNT growth. A comparable process was employed in the conversion of real waste plastics into CNTs and hydrogen.[99] Results obtained by Borsodi *et al.* showed that the presence of Cl (0.3 wt% PVC in waste HDPE) had an adverse effect on CNT formation, whereas the presence of S had less influence with respect to CNT morphologies.[102] El Essawy *et al.* reported a cost-efficient solvent-free procedure to convert PET bottles into carbon nanomaterials through thermal dissociation inside a closed system under autogenic pressure in the presence of additives and/or catalyst, which acted as cluster nuclei for carbon nanomaterials like CNTs and fullerenes. This study was successful in the production and control of the different forms of micro-structured carbon nanomaterials from PET waste through optimization of parameters with regard to amount of catalyst, additives and time.[103] It is clear that the developed processes are limited to laboratory studies and more effort should be made to scale them up. Main challenges encountered by researchers are reactor design and conversion and high operating temperatures, in spite of the sustainable course of waste plastic management. For a sustainable scale-up procedure these challenges and related parameters should be adjusted.[104]

Natural-based monomers for commodity plastics

In order to decrease the negative effect of plastic waste on the environment, one approach would be to decrease the production and use of petroleum derived polymers. Synthesizing polymeric materials from bio-based feedstocks is of interest being more eco-friendly compared with what are currently being used,



Scheme 4. Biodegradable plastic integration.

namely fossil-based feedstocks. Accordingly, this concept was also included into our review. Several natural-polymer based industries were able to compete against the strict competition of synthetics and this success is mainly due to developments in the chemical modification of natural polymers. Among the most important ones are the generation of methods to tune structure, shape and size of the polymers to combine a set of functions and properties for certain applications. There have been trials to apply this knowledge to natural polymers and monomers in order to accomplish required properties, leading to new opinions on possible alternative source to produce polymers.[105–107] The dramatic decrease of fossil resources along with the increase in oil prices induced the search for alternatives, focusing on renewable resources for polymer production.[108,109] Except polymers existing naturally, there exist various monomers that occur naturally, either in free or combined form and can be obtained by cleavage, extraction of de-polymerization from biomass.[110] Agricultural and forest products are widely available and vary structurally, which creates the requirement to reappraise their applications. Huge amounts of effort have been put into the synthesis and characterization of macromolecular materials, synthesized employing renewable resources. Therefore, monomers like furans and terpenes, oligomers such as tannins and rosin and polymers including proteins, cellulose, macromolecules synthesized via microbes have been proved to have features to create various materials through intelligent utilization.[111]

To obtain high-value polymers, studies on applying molecular and process design principles to polymers and monomers obtained naturally or from renewable resources are increasing. Various novel materials are being developed to take the place of petrochemical derivatives.[111–117] Table 1 shows a few of the modifications to some natural-based monomers and their polymers.

Researchers found various applications with polysaccharides and proteins in biodegradable products. There is a lack of natural enzymes in nature for degrading natural polymers. The formation and degradation rate of the final metabolites and the structural complexity of the materials as well as environmental conditions chosen for the degradation are interdependent.[111,146–150] There are enormous opportunities and challenges for the next decades regarding the utilization of non-renewable chemical sources for the synthesis and further construction of polymers. Renewable material sources can be counted as phenolic compounds occurring naturally such as wood, fiber, shell,[151] seed,[152,153] bagasse,[154] empty fruit bunches,[155] acids like lactic acid and alcohols like glycerol and soybean oil.[156–158] There has always been and still is a requirement for the development of new techniques to benefit from renewable resources and synthesize new monomers from to help enable a greener future.

Biodegradation and composting opportunities

Latest trends in the field of biodegradable polymers led to important developments with regard to innovative design strategies and engineering to procure high-performance advanced polymers. Many definitions of biodegradation are based on the application field of the polymers, such as natural environment or biomedical areas.[159] The definition of biodegradation made by Albertsson and Karlsson was if it was an event taking place through the action of enzymes and/or chemical decomposition regarding living organisms and their secretion products.[160] Generally, synthetic polymers are non-biodegradable. Although, polymers with hydrolysable backbones (poly(ester amide)s, poly(amide enamine)s, poly(ortho ester)s, polyurethanes, polycaprolactone, polyamides, polyesters, vinyl polymers) are sensitive to enzymatic biodegradation and hydrolysis.[159] In the simplest definition, biopolymers are developed in nature and are polymers resulting from growth cycles of organisms. Therefore, they are also termed as natural polymers. Synthesis of biopolymers usually involves enzyme catalyzed chain growth polymerization reactions with activated monomers that generally occur within cells through complex metabolic processes. Scheme 3 shows the bio-based polymers' manufacturing route created by Shiam.[161]

It is of no biodegradable value if the product does not culminate in a waste management system using the biodegradability properties.[162,163] Scheme 4, adapted from Song *et al.*[163] shows biodegradable plastic integration with disposal substructures which employs the biodegradable function of the plastic product.

Biodegradable polymers can be classified as bio-based or petrochemical-based depending upon their origins. The former version is based on being produced from natural origins and biodegradable by nature. These natural origins like microorganisms, animals, and plants can be proteins like wheat gluten, casein, gelatin, lipids like animal fats, plant oils and polysaccharides like cellulose, chitin, and starch. An example of this

- Source reduction activities
- Replacing the single-use products in the market with eco-friendly ones
- Extension the life of products by better design and reuse
- Responsibly management throughout the life cycle
- Avoiding unnecessary use where possible
- Reducing the number of components of plastics
- Standardization of the additives to achieve an easy removal
- Measures for sustainable and effective separation, sorting and cleaning
- Government actions to achieve a broader engagement
- R&D for new and sustainable methods of recycling

Scheme 5. Suggested measures for the management of plastics.

category can be natural rubber and some polyesters produced from microorganisms or plants like poly(3-hydroxybutyrate) and polyhydroxyalkanoates or from bio-derived monomers like polylactic acid. Petrochemical-based biodegradable polymers like aliphatic polyesters such as polycaprolactone, polyglycolic acid or polybutylene succinate and aromatic copolyesters such as poly(vinyl alcohol) and polybutylene succinate terephthalate are synthesized via petrochemical refining derived monomers.[163,164] Polylactic acid (PLA) is currently being employed in the packaging of short-shelf life bottles, films and thermoformed containers.[165] A thermoplastic biodegradable polyester poly(ε-caprolactone) (PCL) can be synthesized through chemical conversion of crude oil followed by ring-opening polymerization.[165] PCL has good resistance to chlorine, solvent, oil, and water, has low viscosity and melting point and can be thermally processed easily.

Thermosets are rather tricky in recycling terms since they cannot be remolded after they are once cured and cannot be decomposed thermally with high-temperature heating. Therefore, to recycle and redeploy thermosets, one that can be naturally de-polymerized would be quite useful to lead the way. In a study by Garcia *et al.* recyclable thermosets and organogels were successfully synthesized through one-pot, low-temperature polycondensation between 4,4′-oxydianiline and paraformaldehyde, forming hemiaminal dynamic covalent networks that can cyclize at high temperatures further to produce poly(hexahydrotriazine)s.[166] This study has potential in terms of meeting the requirements for thermoset polymers.

Biodegradable polymers can be used in various fields. Eco-friendly polymers are required in many sectors such as packaging, medicine, controlled drug release and automotive. Bioplastic polymers are promising to serve in the reduction of landfill, material recovery and use of renewable resources. To be able to benefit fully from these materials, effective substructure for strict control of composting, separation, collection and certification as well as widespread public awareness are of significance.

CONCLUSIONS

Plastic products need to be responsibly managed throughout their life cycle so that they are prevented from escaping into the environment by proper waste management, mindful product design and responsible behavior. A number of measures outlined in Scheme 5 can be implemented on a wide scale, from end-user to manufacturers, to manage the design, use and recycling of plastic materials.

Reduce, reuse, recycle (materials) and recover (energy) are the main plastic management strategies in the order of decreasing environmental desirability. The most preferred strategy, reduce, includes source reduction activities, such as reducing the quantity of materials used in production of plastic goods, e.g. using concentrated detergents, extension of the life of products to postpone disposal, avoiding unnecessary use where possible, and replacing single-use products in the market with eco-friendly ones, e.g. using natural-based superabsorbent polymers[167] in disposable diapers instead of petroleum-based ones. Along with these measures, reducing the number of components of plastics, e.g. using a single polymer as much as possible instead of blending multiple polymers in plastic formulations, and reducing the amount of additives used or standardizing them to achieve easy removal from plastics via well-defined procedures may significantly increase the recycling rates.

Some simple measures such as stamping the information written on the labels instead of using labels and label adhesives may facilitate separation, sorting and cleaning operations which are the central and the toughest parts of a plastic recycling process. Government actions are also needed to achieve a broader engagement affecting both the consumers and producers, e.g. plastic products may contain a certain amount of recycled material depending on the field of use.

These measures may not always be economically feasible; however, research should continue to develop proper methods to replace the current ones. There are pros and cons for all plastic management approaches. Ideally, complementary practices of all actions and conservation would be the most ecologically friendly and economically feasible in the long run. We suggest that research should continue to develop sustainable methods of recycling of polymers along with appropriate sorting and identification methods. For instance, new catalysts must be developed to increase the chemical recycling rates of plastics in an energy-saving manner. Most plastics are immiscible with each other; even small amounts of contamination with a different plastic may potentially hinder use of the recycled material. Designing new compatibilizers enhancing the miscibility and physical properties of polymer mixtures is, therefore, important. Almost all current recycling technologies focus on certain thermoplastics, e.g. PET. The rest, in particular cross-linked thermosets, are ignored in recycling operations. Sustained research efforts are important to expand recycling to a diverse array of polymer materials. It seems not to be greener to replace plastics with frequently-mentioned alternatives, such as paper, bio-plastic or, in particular, cotton.[11] Therefore, plastics are indispensable in our lives and will continue to be so; we have to find out better ways to responsively and sustainably design, recycle and recover them.

REFERENCES

1 Zheng Y, Yanful EK and Bassi AS, A review of plastic waste biodegradation. *Crit Rev Biotechnol* **25**:243–250 (2005).

2 Muller RJ, Kleeberg I and Deckwer WD, Biodegradation of polyesters containing aromatic constituents. *J Biotechnol* **86**:87–95 (2001).

3 Bonhomme S, Cuer A, Delort AM, Lemaire J, Sancelme M and Scott G, Environmental biodegradation of polyethylene. *Polym Degrad Stab* **81**:441–452 (2003).

4 Arnaud R, Dabin P, Lemaire J, Al-Malaika S, Chohan S, Coker M *et al.*, Photooxidation and biodegradation of commercial photodegradable polyethylenes. *Polym Degrad Stab* **46**:211–224 (1994).

5 Nishida H and Tokiwa Y, Distribution of poly (b-hydroxybutyrate) and poly (e-caprolactone) aerobic degrading microorganisms in different environments. *J Environ Polym Degrad* **1**:227–233 (1993).

6 Meeker JD, Sathyanarayana S and Swan SH, Phthalates and other additives in plastics: human exposure and associated health outcomes. *Philos Trans R Soc B Biol Sci* **364**:2097–2113 (2009) Available http://rstb.royalsocietypublishing.org/cgi/doi/10.1098/rstb.2008.0268.

7 Francis R, *Recycling of Polymers Methods, Characterization and Applications*. Wiley-VCH, Hoboken, NJ (2016).

8 PlasticsEurope, Plastics - the Facts 2017. *PlasticsEurope* (2018). Available: https://www.plasticseurope.org/application/files/5715/1717/4180/Plastics_the_facts_2017_FINAL_for_website_one_page.pdf [23 May 2018].

9 Hopewell J, Dvorak R and Kosior E, Plastics recycling: challenges and opportunities. *Philos Trans R Soc B Biol Sci* **364**:2115–2126 (2009).

10 Jambeck JR, Geyer R, Wilcox C, Siegler TR, Perryman M, Andrady A *et al.*, Plastic waste inputs from land into the ocean. *Science* **347**:768–771 (2015).

11 Godske B, Plastic bags are more environmentally friendly. *State of Green* (2018). Available: https://stateofgreen.com/en/profiles/state-of-green/news/plastic-bags-are-more-environmentally-friendly [29 April 2018].

12 Smithers R, England's shoppers say goodbye to free plastic bags. *The Guardian* (2015). Available: https://www.theguardian.com/environment/2015/oct/05/englands-shoppers-say-goodbye-to-free-plastic-bags [29 April 2018].

13 Trigg T, England cuts plastic bag usage by 6 billion in 6 months. *Scientific American* (2016). Available: https://blogs.scientificamerican.com/plugged-in/england-cuts-plastic-bag-usage-by-6-billion-in-6-months/ [29 April 2018].

14 McAuley J, France becomes the first country to ban plastic plates and cutlery. *The Washington Post* (2016). Available: https://www.washingtonpost.com/news/worldviews/wp/2016/09/19/france-bans-plastic-plates-and-cutlery/?noredirect=on&utm_term=.f88907fe1f5b [29 April 2018].

15 Wootson CR, Jr, Seattle becomes first major U.S. city to ban straws. *The Washington Post* (2018). Available: https://www.washingtonpost.com/news/post-nation/wp/2018/07/01/seattle-becomes-first-major-u-s-city-to-ban-straws/?noredirect=on&utm_term=.dc9444785166 [29 April 2018].

16 Wu S, *The Seattle Times* (2018). Available: https://www.seattletimes.com/seattle-news/q-heres-what-you-need-to-know/

17 Nikles DE and Farahat MS, New motivation for the depolymerization products derived from poly(ethylene terephthalate) (PET) waste: a review. *Macromol Mater Eng* **290**:13–30 (2005).

18 Soroudi A and Jakubowicz I, Recycling of bioplastics, their blends and biocomposites: a review. *Eur Polym J* **49**:2839–2858 (2013). Available: https://doi.org/10.1016/j.eurpolymj.2013.07.025.

19 Awaja F and Pavel D, Recycling of PET. *Eur Polym J* **41**:1453–1477 (2005).

20 Kumar S, Panda AK and Singh RK, A review on tertiary recycling of high-density polyethylene to fuel. *Resour Conserv Recycl* **55**:893–910 (2011).

21 Al-Salem SM, Lettieri P and Baeyens J, Recycling and recovery routes of plastic solid waste (PSW): a review. *Waste Manage (Oxford)* **29**:2625–2643 (2009).

22 Anuar Sharuddin SD, Abnisa F, Wan Daud WMA and Aroua MK, A review on pyrolysis of plastic wastes. *Energy Convers Manage* **115**:308–326 (2016).

23 Mihut C, Captain DK, Gadala-Maria F and Amiridis MD, Review: recycling of nylon from carpet waste. *Polym Eng Sci* **41**:1457–1470 (2001).

24 Simón D, Borreguero AM, de Lucas A and Rodríguez JF, Recycling of polyurethanes from laboratory to industry, a journey towards the sustainability. *Waste Manage (Oxford)* **76**:147–171 (2018).

25 Curlee TR and Das S, *Plastic Wastes: Management, Control, Recycling, and Disposal*. U.S. Environmental Protection Agency, Washington, DC (1994).

26 Achilias DS, Chemical recycling of polymers. The case of poly(methyl methacrylate). *Int Conf Energy Environ Syst* **2006**:271–276 (2006).

27 McCarthy N, Recycling remains a rarity in eastern Europe. *Statista* (2013). Available: https://www.statista.com/chart/1312/recycling-remains-a-rarity-in-eastern-europe/ [29 April 2018].

28 Karayannidis GP and Achilias DS, Chemical recycling of poly(ethylene terephthalate). *Macromol Mater Eng* **292**:128-146 (2007).

29 Scheirs J, *Polymer Recycling: Science, Technology and Applications*. Wiley, New York (1998).

30 Butkutė R and Miknius L, Properties of residual marine fuel produced by thermolysis from polypropylene waste. *Mater Sci* **21**:1–6 (2015).

31 Achilias DS, Andriotis L, Koutsidis A, Louka DA, Nianias P, Siafaka P *et al.*, Recent advances in the chemical recycling of polymers (PP, PS, LDPE, HDPE, PVC, PC, Nylon, PMMA), in *Material Recycling - Trends and PErspectives*, ed. by Achilias DS. InTech, UK, pp. 3–64 (2012).

32 Jagtap MD, Methods for waste plastic recycling. *Int J Recent Technol Mech Electr Eng* **2**:120–122 (2015).

33 Garcia JM and Robertson ML, The future of plastics recycling. *Science* **358**:870–872 (2017).

34 Sinha V, Patel MR and Patel JV, Pet waste management by chemical recycling: a review. *J Polym Environ* **18**:8–25 (2010).

35 Das P and Tiwari P, Valorization of packaging plastic waste by slow pyrolysis. *Resour Conserv Recycl* **128**:69–77 (2018).

36 Abbas-Abadi MS, Haghighi MN and Yeganeh H, Evaluation of pyrolysis product of virgin high density polyethylene degradation using different process parameters in a stirred reactor. *Fuel Process Technol* **109**:90–95 (2013).

37 Demirbas A, Pyrolysis of municipal plastic wastes for recovery of gasoline-range hydrocarbons. *J Anal Appl Pyrolysis* **72**:97–102 (2004).

38 Aboulkas A, Makayssi T, Bilali L, El Harfi K, Nadifiyine M and Benchanaa M, Co-pyrolysis of oil shale and plastics: influence of pyrolysis parameters on the product yields. *Fuel Process Technol* **96**:209–213 (2012).

39 Adrados A, de Marco I, Caballero BM, López A, Laresgoiti MF and Torres A, Pyrolysis of plastic packaging waste: a comparison of plastic residuals from material recovery facilities with simulated plastic waste. *Waste Manage (Oxford)* **32**:826–832 (2012).

40 Domínguez A, Blanco CG, Barriocanal C, Alvarez R and Díez MA, Gas chromatographic study of the volatile products from co-pyrolysis of coal and polyethylene wastes. *J Chromatogr A* **918**:135–144 (2001).

41 Singh S, Wu C and Williams PT, Pyrolysis of waste materials using TGA-MS and TGA-FTIR as complementary characterisation techniques. *J Anal Appl Pyrolysis* **94**:99–107 (2012).

42 Miandad R, Barakat MA, Aburiazaiza AS, Rehan M and Nizami AS, Catalytic pyrolysis of plastic waste: a review. *Process Saf Environ Prot* **102**:822–838 (2016).

43 Shah SH, Khan ZM, Raja IA, Mahmood Q, Bhatti ZA, Khan J *et al.*, Low temperature conversion of plastic waste into light hydrocarbons. *J Hazard Mater* **179**:15–20 (2010).

44 Stelmachowski M and Slowinski K, Thermal and thermo-catalytic conversion of waste polyolefins to fuel-like mixture of hydrocarbons. *Chem Process Eng* **33**:185–198 (2012).
45 Yousif E and Haddad R, Photodegradation and photostabilization of polymers, especially polystyrene: review. *Springerplus* **2**:1–32 (2013).
46 Daglen BC and Tyler DR, Photodegradable plastics: end-of-life design principles. *Green Chem Lett Rev* **3**:69–82 (2010).
47 Shang J, Chai M and Zhu Y, Photocatalytic degradation of polystyrene plastic under fluorescent light. *Environ Sci Technol* **37**:4494–4499 (2003).
48 Vijayalakshmi SP and Madras G, Effect of temperature on the ultrasonic degradation of polyacrylamide and poly(ethylene oxide). *Polym Degrad Stab* **84**:341–344 (2004).
49 Sivalingam G, Vijayalakshmi SP and Madras G, Enzymatic and thermal degradation of poly(ε-caprolactone), poly(D,L-lactide), and their blends. *Ind Eng Chem Res* **43**:7702–7709 (2004).
50 Price GJ and Smith PF, Ultrasonic degradation of polymer-solutions: 2. The effect of temperature, ultrasound intensity and dissolved-gases on polystyrene in toluene. *Polymer* **34**:4111–4117 (1993).
51 Madras G and Chattopadhyay S, Effect of benzoyl peroxide on the ultrasonic degradation of poly(vinyl acetate). *Polym Degrad Stab* **73**:33–38 (2001).
52 Grönroos A, Pirkonen P and Ruppert O, Ultrasonic depolymerization of aqueous carboxymethylcellulose. *Ultrason Sonochem* **11**:9–12 (2004).
53 Chakraborty J, Sarkar J, Kumar R and Madras G, Ultrasonic degradation of polybutadiene and isotactic polypropylene. *Polym Degrad Stab* **85**:555–558 (2004).
54 Aishwarya KN and Sindhu N, Microwave assisted pyrolysis of plastic waste. *Procedia Technol* **25**:990–997 (2016). Available: http://linkinghub.elsevier.com/retrieve/pii/S221201731630545X.
55 Liu Z, Liu R, Wang Y, Fan X and Tao C, Microwave-assisted degradation of waste polyethyleneterephthalate (PET) at atmospheric pressure using silicon carbide as power modulator, in *Proceeding of 2011 International Conference on Remote Sensing, Environment and Transportation Engineering*. IEEE, Nanjing, China, pp. 3276–3280 (2011).
56 Undri A, Rosi L, Frediani M and Frediani P, Microwave pyrolysis of polymeric materials, in *Microw Heat*, ed. by Usha C. InTech, UK, pp. 207–232 (2011).
57 Nikje MMA and Askarzadeh M, Controllable microwave-assisted polycarbonate waste chemical recycling. *Prog Rubber Plast Recycl Technol* **29**:169–176 (2013).
58 Bäckström E, Odelius K and Hakkarainen M, Trash to treasure: microwave-assisted conversion of polyethylene to functional chemicals. *Ind Eng Chem Res* **56**:14814–14821 (2017).
59 Alavi Nikje MM, Nikrah M and Mohammadi FHA, Microwave-assisted polyurethane bond cleavage via hydroglycolysis process at atmospheric pressure. *J Cell Plast* **44**:367–380 (2008).
60 Appiah JK, Berko-Boateng VN and Tagbor TA, Use of waste plastic materials for road construction in Ghana. *Case Stud Constr Mater* **6**:1–7 (2017).
61 Kalantar ZN, Karim MR and Mahrez A, A review of using waste and virgin polymer in pavement. *Constr Build Mater* **33**:55–62 (2012).
62 Becker Y, Mendez MP and Rodriguez Y, Polymer modified asphalt. *Vis Technol* **9**:39–50 (2001).
63 Sharma R, Sharma M, Sharma R and Sharma V, The impact of incinerators on human health and environment. *Rev Environ Health* **28**:67–72 (2013).
64 Nikles DE and Farahat MS, New motivation for the depolymerization products derived from poly(ethylene terephthalate) (PET) waste: a review. *Macromol Mater Eng* **290**:13–30 (2005).
65 Jankauskaite V, Macijauskas G and Lygaitis R, Polyethylene terephthalate waste recycling and application possibilities: a review. *Mater Sci* **14**:119–127 (2009).
66 Ravichandran S, Bouldin RM, Kumar J and Nagarajan R, A renewable waste material for the synthesis of a novel non-halogenated flame retardant polymer. *J Cleaner Prod* **19**:454–458 (2011).
67 Wu Z, Kong L, Hu H, Tian S and Xiong Y, Adsorption performance of hollow spherical sludge carbon prepared from sewage sludge and polystyrene foam wastes. *ACS Sustainable Chem Eng* **3**:552–558 (2015).
68 Liu D and Liu J, Converting waste expanded polystyrene into polymeric azo dyes containing the sulfonamide group. *J Mater Cycles Waste Manage* **16**:557–565 (2014).
69 You C, Liao S, Qiao X, Zeng X, Liu F, Zheng R *et al.*, Conversion of polystyrene foam to a high-performance doped carbon catalyst with ultrahigh surface area and hierarchical porous structures for oxygen reduction. *J Mater Chem A* **2**:12240–12246 (2014).
70 Fonseca WS, Meng X and Deng D, Trash to treasure: transforming waste polystyrene cups into negative electrode materials for sodium ion batteries. *ACS Sustainable Chem Eng* **3**:2153–2159 (2015).
71 Zhang MR, Fang CQ, Zhou SS, Cheng YL and Hu JB, Modification of asphalt by dispersing waste polyethylene and carbon fibers in it. *Xinxing Tan Cailiao/New Carbon Mater* **31**:424–430 (2016).
72 Lee SH, Balasubramanian M and Kim JK, Dynamic reaction inside co-rotating twin screw extruder. I. Truck tire model material/polypropylene blends. *Appl Polym Sci* **106**:3193–3208 (2007).
73 Hong CK and Isayev AI, Blends of ultrasonically devulcanized and virgin carbon black filled NR. *J Mater Sci* **37**:385–388 (2002).
74 Xin ZX, Zhang ZX, Pal K, Kang DJ, Lee SH and Kim JK, Effects of waste ground rubber tire powder (WGRT) and chemical blowing agent content on the cell morphology and physicomechanical properties of injection-molded polypropylene/wgrt foams. *J Vinyl Add Tech* **15**:275–280 (2009).
75 Jeong KM, Hong YJ, Saha P, Park SH and Kim JK, Novel polymer composites from waste ethylene-propylene-diene-monomer rubber by supercritical CO2 foaming technology. *Waste Manage Res* **32**:1113–1122 (2014).
76 Kumar A, Choudhary V, Khanna R, Cayumil R, Ikram-ul-Haq M, Sahajwalla V *et al.*, Recycling polymeric waste from electronic and automotive sectors into value added products. *Front Environ Sci Eng* **11**:4 (2017).
77 Kasper AC, Berselli GBT, Freitas BD, Tenório JAS, Bernardes AM and Veit HM, Printed wiring boards for mobile phones: characterization and recycling of copper. *Waste Manage (Oxford)* **31**:2536–2545 (2011).
78 Widmer R, Oswald-Krapf H, Sinha-Khetriwal D, Schnellmann M and Böni H, Global perspectives on e-waste. *Environ Impact Assess Rev* **25**:436–458 (2005).
79 Li A, Zhang Q, Zhang G, Chen J, Fei Z and Liu F, Adsorption of phenolic compounds from aqueous solutions by a water-compatible hypercrosslinked polymeric adsorbent. *Chemosphere* **47**:981–989 (2002).
80 Kovin TEKIH, Alsewailem FD and Aljlil SA, Recycled polymer / clay composites for heavy-metals adsorption. *Mater Technol* **47**:525–529 (2013).
81 Metz B, Davidson O, De Coninck M, Loos M and Meyer L eds, *Special Report on Carbon Dioxide Capture and Storage*. Cambridge University Press, Cambridge (2005).
82 OSPAR. Carbon Capture and Storage **325**:1647–52 (2015). Available: http://www.ospar.org/content/content.asp?menu=00810305320000_000000_000000
83 Adhikari S and Fernando S, Hydrogen membrane separation techniques. *Ind Eng Chem Res* **45**:875–881 (2006).
84 Xu C and Hedin N, Microporous adsorbents for CO2capture - a case for microporous polymers? *Mater Today* **17**:397–403 (2014).
85 Wu H, Chua YS, Krungleviciute V, Tyagi M, Chen P, Yildirim T *et al.*, Unusual and highly tunable missing-linker defects in zirconium metal-organic framework UiO-66 and their important effects on gas adsorption. *J Am Chem Soc* **135**:10525–10532 (2013).
86 Samanta A, Zhao A, Shimizu GKH, Sarkar P and Gupta R, Post-combustion CO2 capture using solid sorbents: a review. *Ind Eng Chem Res* **51**:1438–1463 (2012).
87 Sneddon G, McGlynn JC, Neumann MS, Aydin HM, Yiu HHP and Ganin AY, Aminated poly(vinyl chloride) solid state adsorbents with hydrophobic function for post-combustion CO $_2$ capture. *J Mater Chem A* **5**:11864–11872 (2017).
88 Kan A and Demirboğa R, A new technique of processing for waste-expanded polystyrene foams as aggregates. *J Mater Process Technol* **209**:2994–3000 (2009).
89 Fu Z, Jia J, Li J and Liu C, Transforming waste expanded polystyrene foam into hyper-crosslinked polymers for carbon dioxide capture and separation. *Chem Eng J* **323**:557–564 (2017).
90 Chen A, Li Y, Yu Y, Li Y, Zhang L, Lv H *et al.*, Mesoporous carbonaceous materials prepared from used cigarette filters for efficient phenol adsorption and CO $_2$ capture. *RSC Adv* **5**:107299–107306 (2015).
91 Sanz-Pérez ES, Arencibia A, Sanz R and Calleja G, An investigation of the textural properties of mesostructured silica-based adsorbents for predicting CO2 adsorption capacity. *RSC Adv* **5**:103147–103154 (2015).

92 Pol VG, Upcycling: converting waste plastics into paramagnetic, conducting, solid, pure carbon microspheres. *Environ Sci Technol* **44**:4753–4759 (2010).

93 Yang X, Li C, Wang W, Yang B, Zhang S and Qian Y, A chemical route from PTFE to amorphous carbon nanospheres in supercritical water. *Chem Commun* **3631760**:342–343 (2004).

94 Zou G, Yu D, Jiang C, Xi G, Qian Y and Zhang H, A mild reduction route to PTFE degradation at low temperature. *Chem Lett* **33**:1150–1151 (2004).

95 Chernozatonskii LA, Kukovitskii EF, Musatov AL, Ormont AB, Izraeliants KR and L'vov SG, Carbon crooked nanotube layers of polyethylene: synthesis, structure and electron emission. *Carbon* **36**:6–713 (1998).

96 Liu J, Jiang Z, Yu H and Tang T, Catalytic pyrolysis of polypropylene to synthesize carbon nanotubes and hydrogen through a two-stage process. *Polym Degrad Stab* **96**:1711–1719 (2011).

97 Tang T, Chen X, Meng X, Chen H and Ding Y, Synthesis of multi-walled carbon nanotubes by catalytic combustion of polypropylene. *Angew Chem Int Ed* **44**:1517–1520 (2005).

98 Zhang J, Li J, Cao J and Qian Y, Synthesis and characterization of larger diameter carbon nanotubes from catalytic pyrolysis of polypropylene. *Mater Lett* **62**:1839–1842 (2008).

99 Wu C, Nahil MA, Miskolczi N, Huang J and Williams PT, Processing real-world waste plastics by pyrolysis-reforming for hydrogen and high-value carbon nanotubes. *Environ Sci Technol* **48**:819–826 (2014).

100 Quan C, Li A and Gao N, Synthesis of carbon nanotubes and porous carbons from printed circuit board waste pyrolysis oil. *J Hazard Mater* **179**:911–917 (2010).

101 Nahil MA, Wu C and Williams PT, Influence of metal addition to Ni-based catalysts for the co-production of carbon nanotubes and hydrogen from the thermal processing of waste polypropylene. *Fuel Process Technol* **130**:46–53 (2015).

102 Borsodi N, Szentes A, Miskolczi N, Wu C and Liu X, Carbon nanotubes synthetized from gaseous products of waste polymer pyrolysis and their application. *J Anal Appl Pyrolysis* **120**:304–313 (2016).

103 El Essawy NA, Konsowa AH, Elnouby M and Farag HA, A novel one-step synthesis for carbon-based nanomaterials from polyethylene terephthalate (PET) bottles waste. *J Air Waste Manag Assoc* **67**:358–370 (2017).

104 Mukherjee A, Debnath B, Ghosh SK. Carbon nanotubes as a resourceful product derived from waste plastic – a review. 2016.

105 Mark Hoffman D and Caley LE, Polymer blends as high explosive binders. *Polym Eng Sci* **26**:1489–1499 (1986).

106 Wirth JG, Polymer research and development in the 1900s - the challenge of high added value materials. *Prog Polym Sci* **19**:947–958 (1994).

107 Pillai CKS, Challenges for natural monomers and polymers: novel design strategies and engineering to develop advanced polymers. *Des Monomers Polym* **13**:87–121 (2010).

108 Pillai CKS, High-performance and functional materials from natural monomer and polymers, in *Handbook of Engineering Polymeric Materials*, ed. by Cheremisinoff NP. Marcel Dekker Inc., New York, pp. 411–438 (1996).

109 Williams CK and Hillmyer MA, Polymers from renewable resources: a perspective for a special issue of polymer reviews. *Polym Rev* **48**:1–10 (2008).

110 Carraher CE Jr and Sperling LH eds, Polymer applications of renewable-resource materials, in *Polymer Science and Technology*. Plenum Press, New York (1981).

111 Pillai CKS, Plastic materials – the resource crunch and transitions: can monomers and polymers from renewable resources meet the demand? *Pop Plast Packag* **54**:41–54 (2009).

112 Mohanty AK, Misra M and Hinrichsen G, Biofibres, biodegradable polymers and biocomposites: an overview. *Macromol Mater Eng* **276–277**:1–24 (2000).

113 Bogoeva-Gaceva G, Avella M, Malinconico M, Buzarovska A, Grozdanov A, Gentile G *et al.*, Natural fiber eco-composites. *Polym Compos* **28**:98–107 (2007).

114 Araki T, Shibayama M and Tran-Cong Q eds, *Structure and Properties of Multiphase Polymeric Materials*. Marcel Dekker Inc., New York (1998).

115 Postek MT, Vladar A, Dagata J, Farkas N, Ming B, Sabo R *et al.*, Cellulose nanocrystals the next big nano-thing? in *Proceedings of SPIE 7042, Instrumentation, Metrology, and Standards for Nanomanufacturing II, 4072D*. International Society for Optical Engineering, NanoScience + Engineering, San Diego, CA, p. 70420D (2008). Available: http://proceedings.spiedigitallibrary.org/proceeding.aspx?doi=10.1117/12.797575.

116 Cunliffe D, Pennadam S and Alexander C, Synthetic and biological polymers - merging the interface. *Eur Polym J* **40**:5–25 (2004).

117 Kobayashi S and Uyama H, Biomacromolecules and bio-related macromolecules. *Macromol Chem Phys* **204**:235–256 (2003).

118 Belgacem M and Gandini A, *Monomers, Polymers and Composites from Renewable Resources*. Elsevier, Amsterdam, pp. 289–304 (2008).

119 SadAbadi H and Packirisamy M, Nano-integrated suspended polymeric microfluidics (SPMF) Platform for ultra-sensitive bio-molecular recognition of bovine growth hormones. *Sci Rep* **7**:1–10 (2017).

120 Lu Y and Larock RC, Novel polymeric materials from vegetable oils and vinyl monomers: preparation, properties, and applications. *ChemSusChem* **2**:136–147 (2009).

121 Meier MAR, Metzger JO and Schubert US, Plant oil renewable resources as green alternatives in polymer science. *Chem Soc Rev* **36**:1788–1802 (2007).

122 Petrovic ZS, Polyurethanes from vegetable oils. *Polym Rev* **48**:109–155 (2008).

123 Montero De Espinosa L and MAR M, Plant oils: the perfect renewable resource for polymer science?! *Eur Polym J* **47**:837–852 (2011). Available: https://doi.org/10.1016/j.eurpolymj.2010.11.020.

124 Lligadas G, Ronda JC, Galià M and Cádiz V, Renewable polymeric materials from vegetable oils: a perspective. *Mater Today* **16**:337–343 (2013).

125 Mosiewicki MA and Aranguren MI, A short review on novel biocomposites based on plant oil precursors. *Eur Polym J* **49**:1243–1256 (2013).

126 Guner FS, Yagci Y and Erciyes AT, Polymers from triglyceride oils. *Prog Polym Sci* **31**:633–670 (2006).

127 Anderson AJ and Dawes EA, Occurrence, metabolism, metabolic role, and industrial uses of bacterial polyhydroxyalkanoates. *Microbiol Rev* **54**:450–472 (1990).

128 Lee SY, Bacterial Polyb ydroxyalkanoates. *Biotechnol Bioeng* **49**:1–14 (1996).

129 Jacquel N, Lo CW, Wei YH, Wu HS and Wang SS, Isolation and purification of bacterial poly(3-hydroxyalkanoates). *Biochem Eng J* **39**:15–27 (2008).

130 Gandini A and Lacerda TM, From monomers to polymers from renewable resources: recent advances. *Prog Polym Sci* **48**:1–39 (2015). Available: https://doi.org/10.1016/j.progpolymsci.2014.11.002.

131 Pang J, Zheng M, Sun R, Wang A, Wang X and Zhang T, Synthesis of ethylene glycol and terephthalic acid from biomass for producing PET. *Green Chem* **18**:342–359 (2016).

132 Wang A and Zhang TAO, One-pot conversion of cellulose tungsten-based catalysts. *Acc Chem Res* **46**:1377–1386 (2013).

133 Ji N, Zhang T, Zheng M, Wang A, Wang H, Wang X *et al.*, Direct catalytic conversion of cellulose into ethylene glycol using nickel-promoted tungsten carbide catalysts. *Angew Chem Int Ed* **47**:8510–8513 (2008).

134 McKenna R and Nielsen DR, Styrene biosynthesis from glucose by engineered *E. coli*. *Metab Eng* **13**:544–554 (2011).

135 Ranucci E, Liu Y, Söderqvist Lindblad M and Albertsson A-C, New biodegradable polymers from renewable sources. High molecular weight poly(ester carbonate)s from succinic acid and 1,3-propanediol. *Macromol Rapid Commun* **21**:680–684 (2000).

136 Pinazo JM, Domine ME, Parvulescu V and Petru F, Sustainability metrics for succinic acid production: a comparison between biomass-based and petrochemical routes. *Catal Today* **239**:17–24 (2015).

137 Bechthold I, Bretz K, Kabasci S, Kopitzky R and Springer A, Succinic acid: a new platform chemical for biobased polymers from renewable resources. *Chem Eng Technol* **31**:647–654 (2008).

138 Rose M and Palkovits R, Isosorbide as a renewable platform chemical for versatile applications-quo vadis? *ChemSusChem* **5**:167–176 (2012).

139 van Es DS, Rigid biobased building blocks. *J Renewable Mater* **1**:61–72 (2013).

140 Fenouillot F, Rousseau A, Colomines G, Saint-Loup R and Pascault JP, Polymers from renewable 1,4:3,6-dianhydrohexitols (isosorbide, isomannide and isoidide): a review. *Prog Polym Sci* **35**:578–622 (2010).

141 Mialon L, Pemba AG and Miller SA, Biorenewable polyethylene terephthalate mimics derived from lignin and acetic acid. *Green Chem* **12**:1704–1706 (2010).

142 Mialon L, Vanderhenst R, Pemba AG and Miller SA, Polyalkylenehydroxybenzoates (PAHBs): biorenewable aromatic/aliphatic polyesters from lignin. *Macromol Rapid Commun* **32**:1386–1392 (2011).

143 Aouf C, Lecomte J, Villeneuve P, Dubreucq E and Fulcrand H, Chemo-enzymatic functionalization of gallic and vanillic acids: synthesis of bio-based epoxy resins prepolymers. *Green Chem* **14**:2328–2336 (2012).

144 da Silva EAB, Zabkova M, Araújo JD, Cateto CA, Barreiro MF, Belgacem MN *et al.*, An integrated process to produce vanillin and lignin-based polyurethanes from Kraft lignin. *Chem Eng Res Des* **87**:1276–1292 (2009).

145 Pinto PCR and Borges EA, Insights into oxidative conversion of lignin to high-added-value phenolic aldehydes. *Ind Eng Chem Res* **50**:741–748 (2011).

146 Klemm D, Heublein B, Fink HP and Bohn A, Cellulose: fascinating biopolymer and sustainable raw material. *Angew Chem Int Ed* **44**:3358–3393 (2005).

147 Hendriks ATWM and Zeeman G, Pretreatments to enhance the digestibility of lignocellulosic biomass. *Bioresour Technol* **100**:10–18 (2009).

148 Poole AJ, Church JS and Huson MG, Environmentally sustainable fibers from regenerated protein. *Biomacromolecules* **10**:1–8 (2009).

149 Heino J, Huhtala M, Käpylä J and Johnson MS, Evolution of collagen-based adhesion systems. *Int J Biochem Cell Biol* **41**:341–348 (2009).

150 Wang Z-F, Fang L, Zhang K-X and Fu X, Application and research progress of starch in polymer materials. *J Clin Rehabil Tissue Eng Res* **12**:3789 (2008).

151 Wasserman D and Dawson CR, Comparison of the monophenol isolated from commercial raw cashew nutshell liquid and from commercial cardanol. *Ind Eng Chem* **37**:395–399 (1945).

152 Kozlowska H, Rotkiewicz DA, Zadernowski R and Sosulski FW, Phenolic acids in rapeseed and mustard. *J Am Oil Chem Soc* **60**:1119–1123 (1983).

153 Zahradníková L, Schmidt Š and Sékelyová Z, Fractionation and identification of some phenolics extracted from evening primrose seed meal. *Czech J Food Sci* **26**:58–64 (1998).

154 RíOs Leal E, RodríGuez-VáZquez R and Galindo T, Separation of phenolic compounds from sugarcane bagasse pith and their determination by HPLC. *J Wood Chem Technol* **14**:369–382 (1994).

155 Kawser MD and Nash F, Oil palm shell as a source of phenol. *J Oil Palm Res* **12**:86–94 (2000).

156 Meier MAR, Metathesis with oleochemicals: new approaches for the utilization of plant oils as renewable resources in polymer science. *Macromol Chem Phys* **210**:1073–1079 (2009).

157 Behr A, Eilting J, Irawadi K, Leschinski J and Lindner F, Improved utilisation of renewable resources: new important derivatives of glycerol. *Green Chem* **10**:13–30 (2008).

158 Lochab B, Varma IK and Bijwea J, Sustainable polymers derived from naturally occurring materials. *Adv Mater Phys Chem* **2**:221–225 (2012).

159 Luckachan GE and Pillai CKS, Biodegradable polymers - a review on recent trends and emerging perspectives. *J Polym Environ* **19**:637–676 (2011).

160 Albertsson AC and Karlsson S, Chemistry and biochemistry of polymer biodegradation, in *Chemistry and Technology of Biodegradable Polymers*, ed. by Griffin GJL. Blackie Academic & Professional, Glasgow, pp. 7–17 (1994).

161 Shivam P, Recent developments on biodegradable polymers and their future trends. *Int Res J Sci Eng* **4**:17–26 (2016).

162 Narayan R, Biodegradation of polymeric materials (anthropogenic macromolecules) during composting, in *Science and Engineering of Composting: Design, Environmental, Microbiological and Utilization Aspects*, ed. by HAJ H and Keener HM. Renaissance Publications, Ohio, p. 339 (1993).

163 Song JH, Murphy RJ, Narayan R and Davies GBH, Biodegradable and compostable alternatives to conventional plastics. *Philos Trans R Soc B Biol Sci* **364**:2127–2139 (2009).

164 Smith R, *Biodegradable Polymers for Industrial Applications*, 1st edn. Woodhead Publishing, Cambridge (2005). Available: https://www.elsevier.com/books/biodegradable-polymers-for-industrialapplications/ smith/978-1-85573-934-5.

165 Gross RA and Kalra B, Biodegradable polymers for the environment. *Science* **297**:803–807 (2002).

166 García JM, Jones GO, Virwani K, McCloskey BD, Boday DJ, Ter Huurne GM *et al.*, Recyclable, strong thermosets and organogels via paraformaldehyde condensation with diamines. *Science* **344**:732–735 (2014).

167 Hayrabolulu H, Şen M, Çelik G and Kavakli PA, Synthesis of carboxylated locust bean gum hydrogels by ionizing radiation. *Radiat Phys Chem* **94**:240–244 (2014).