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Material circularity and the role of the chemical sciences as a key enabler of a sustainable post-trash age

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ABSTRACT

Approaching material circularity through minimising waste is an essential component of strategies to secure sustainability of the planetary environment. Elaborations of the 3R waste hierarchy (reduce, reuse, recycle), including circular economy, 'zero waste' and zero discharge movements, signpost pathways towards overcoming the challenge. Potential technical solutions require major inputs from the chemical sciences, in strong cooperation with others, to deliver the material basis of sustainability. This must address not only the question of limited resources, but also the totality of consequences connected to massive material and product flows. Three examples, involving aluminium, plastics and textiles, explored using the systems-oriented concept map extension (SOCME) tool, illustrate the complexity of problems and need for integration of chemistry-based solutions into achieving a post-trash approach to sustainability.

1. Introduction

'Waste' commonly refers to material that is 'thrown away' – either collected as 'trash' or discarded in the environment – as material without economic value. However, since matter can be neither created nor destroyed (Law of Conservation of Matter) (Lavoisier, 1789), there is no such thing as 'away'. When we throw anything away, it must go somewhere (Leonard and Conrad, 2010) (Fig. 1). Anthropogenic waste in all its forms, as broadly defined below, is a substantial contributor to a range of planetary-scale environmental crises that are unfolding with increasing rapidity.

In recent decades, policies in some countries have shifted from viewing discarded material as a worthless nuisance to treating it as a valuable resource for further use (European Resource Efficiency Platform, 2014). While often still to be fully implemented, the shift in policies is an important element in a broader approach, symbolized in the proposal (Hopf et al., 2019) to adopt the term 'post-trash', which needs to be adopted by society as a whole. This must represent a changed ambition not only for how waste is regarded but also for ensuring that steps along the entire life cycle of products, i.e. a chain of material sourcing, processing, use and recovery/reuse or end-of-life disposal, are made sustainable in terms of resources and planetary impacts. Producing 'zero waste', while it can never be 100% achievable, has become an aspirational ideal of many initiatives (Zero Waste International Alliance, 2020; Hannon and Zaman, 2018; Kümmerer et al., 2018).

As the science and industry concerned with transformations of matter, chemistry is central to this 'post-trash' reorientation, working in strong cooperation with other disciplines to deliver the material basis of sustainability. This article overviews what is known about the complex challenges involved in addressing not only the question of limited resources, but also the totality of consequences connected to massive material and product flows. Synthesising information from diverse fields, it highlights successes to date and gaps in knowledge or practice still needing to be filled, exemplified by examination of three specific

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cases.

2. Scope, scale and impacts of waste

Waste is generally regarded as any material discarded because it is a product, by-product or breakdown product that has served its purpose, is spent or no longer of use to the holder, or is regarded by others as unusable or lacking value. While most frequently applied to solid materials and contaminated liquids whose disposal needs to be managed, the noun waste also needs to be understood to refer to two other categories. One is 'pollution', comprising gases, volatile materials and microparticulate aerosols and dusts discarded by emission into the atmosphere and fluids that exude into water courses, as intended or unintended by-products or end products of processes conducted by people. The second is expressed in using the verb 'to waste', meaning 'to use or expend carelessly, extravagantly, or to no purpose', examples of which include the excessive or imprudent uses of antibiotics, fertilizers and pesticides and, as exemplified here, of materials such as plastics and textiles.

A further important dimension concerns avoiding wastage of the accessible and useable stocks of scarce natural resources (European Commission, 2017; Matlin et al., 2019a), often found localised in a few high-concentration deposits. Their mining, exploitation and dispersal through waste disposal processes may result in low-concentration distributions making recovery impractical.

Globally, municipal solid waste (MSW: comprising residential, commercial and institutional waste) totalled 2.01 billion tonnes per year in 2016, predicted to increase by 70% to 3.40 billion tonnes per year by 2050 if there are no changes in present practices (Kaza et al., 2018). However, MSW is only part of the overall magnitude of global waste (Makower and Pike, 2009). For example, in 2016 the combination of all waste generated in the European Union (EU) alone, from household, manufacturing, construction, water supply and energy activities amounted to over 2.5 billion tonnes, of which only 10% was MSW (Eurostat, 2020).

Concerns (Meadows et al., 1972; World Commission on Environment and Development, 1987) about the limits of resources, the Earth's carrying capacity for its population and the increasing levels of anthropogenic pollutants were forerunners of the concept (Steffen et al., 2015a) of 'planetary boundaries'. Most of these boundaries have chemistry indicators, including the biogeochemical flows of carbon, nitrogen and phosphorus and novel entities (synthetic chemicals) which are major contributors to currently accelerating planetary changes (Steffen et al., 2015b). It is urgent to reduce these impacts, but the commitment made by countries in 2002, to minimize by 2020 the adverse effects of chemicals and pollutants passing into the environment, will not be achieved (Halpaap and Dittkrist, 2019).

3. Chemistry's role in moving to a post-trash world

3.1. Material circularity and chemistry

The '3R' principles – reduce, reuse and recycle – first emerged in the 1970s (Gordon, 2015). While the list of Rs has proliferated (Gharfalkar et al., 2016), the underlying principles have become core concepts in a number of overlapping and interconnected sustainability movements that focus on waste management (Sakai et al., 2011), reducing waste,

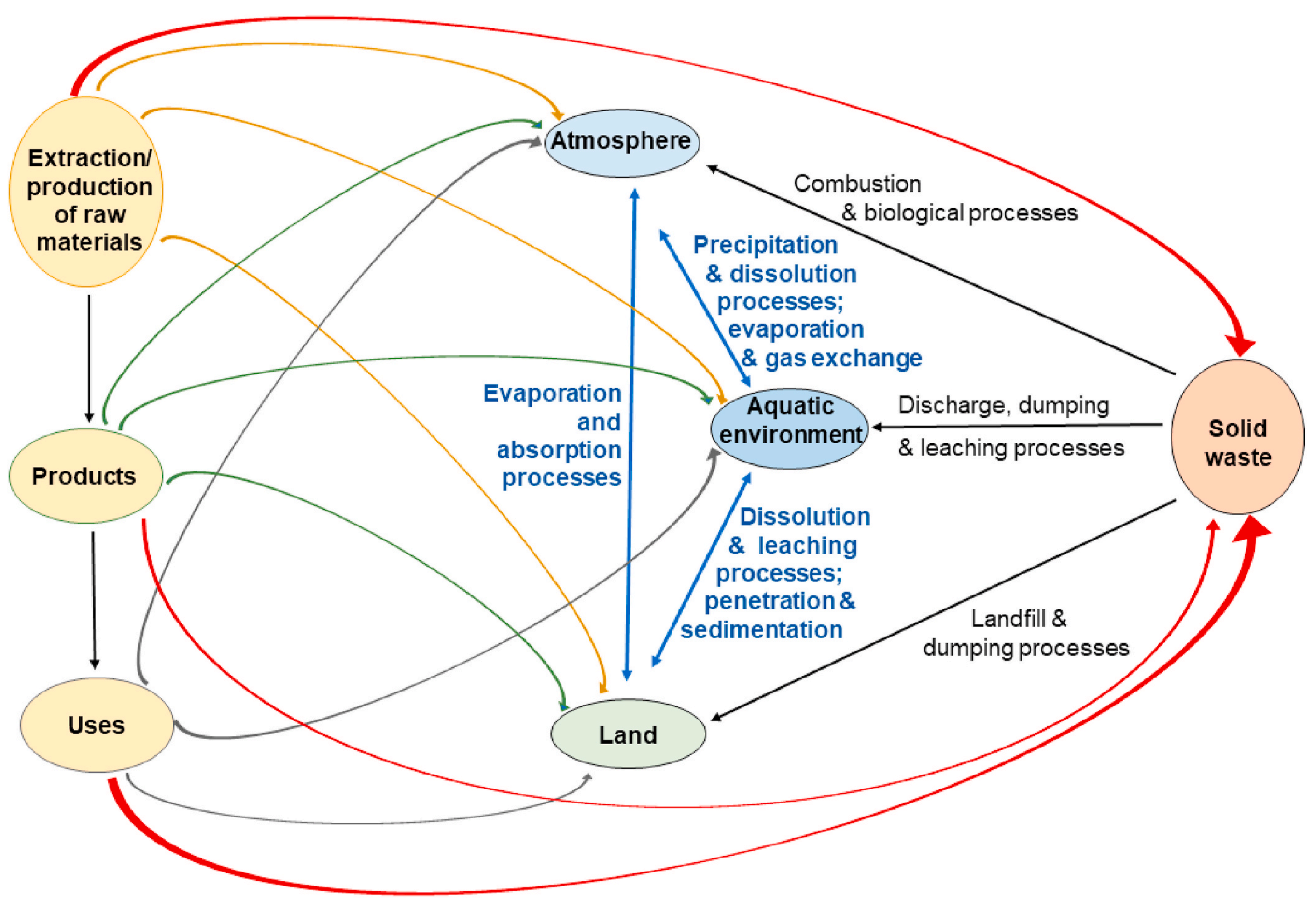

Fig. 1. Sources, conversions of and interconnections between solid, liquid and gas forms of waste. Solid, liquid and gaseous wastes from human activities interact with land (organized landfill or informal dumping processes) aquatic systems (discharge, dumping or leaching processes) and the atmosphere (combustion or biological digestion) and the waste materials may be further transformed by chemical and biological processes.

conserving stocks and deriving utility from material that was previously regarded as without value. The circular economy approach adopted by the EU (European Commission, 2020a, 2020b) and elsewhere (Ellen MacArthur Foundation, 2017a) aims to break the global 'take-make-consume-dispose' linear model (Lacy and Rutqvist, 2015). It offers instead an economically practical material circularity, in which material throughput is minimised and material that is used and outputted is recaptured and returned to further uses as much as possible. At the level of commercial operations, material circularity indicators (Ellen MacArthur Foundation, 2017b) have been developed to measure the effectiveness of processes adopted. However, it is still necessary to ensure that the actual environmental impacts of the circular economy work toward sustainability (Korhonen et al., 2018).

A specific, chemistry-based partial correlate of the '3R' concept, with a strong emphasis on 'reduce', has been seen in the emergence of 'green chemistry' from the early 1990s. Focusing on synthesis, it aims towards the prevention of pollution through innovative design of production technologies (Erythropel et al., 2018). 'Sustainable chemistry' is a broader field that includes 'green chemistry' (Centi and Perathoner, 2009). It adopts systems thinking and cross disciplinary approaches, as advocated in 'one-world chemistry' (Matlin et al., 2016), and new business models to encompass the entire life cycle of materials and reduce the use of all resources and materials flows (Elser and Ulbrich, 2017; Kümmerer, 2017). Chemical leasing (OECD, 2019) has been adopted in some countries (UNIDO, 2019) to provide a strong incentive for both supplier and user to minimize the amount of chemical consumed and maximise the amount returned (OECD, 2017). Circular chemistry (Keijer et al., 2019) incorporates eleven hierarchy levels and prioritises reduce use of materials and developing novel reactions to reuse and recycle them. However, green and circular chemistry do not encompass the entire waste system and take account, for example, of total material, product and energy flows, economic costs and environmental impacts of returning/recycling solvents and other chemicals and the post-use fate of complex materials. A comprehensive approach based on global material circularity and the nature and magnitude of energy generation, consumption and waste outputs, is necessary to incorporate these factors.

3.2. Hierarchies of waste

A shared characteristic of many approaches to minimising waste and promoting circularity in the management of materials has been the emergence of waste hierarchies (Lansink, 2017) such as that seen in the waste directive (European Commission, 2008) of the European Commission (EC), which has six tiers: prevent, reuse, recycle, recover energy, incinerate and landfill. Elaborations of hierarchies for general and hazardous waste (Zero Waste Canada, 2018) have aimed to encourage the change of mindset from waste management to resource management, including prioritisation (Dickinson, 2019) of 'material and chemical recovery' over 'simple energy recovery' and orientation as a 'sustainability hierarchy', prioritizing sustainability of resources and emphasising waste prevention options (Perket, 2010).

4. Case studies

Overall achievement of sustainability requires integration of considerations from a range of overlapping approaches and tools that include the circular economy, life cycle assessment (LCA), waste minimisation and waste hierarchy and that are promoted, stimulated and regulated through economic and legal frameworks and social attitudes and cultures. A number of publications have emphasised that the multiple roles that the chemical sciences must play require innovative solutions that begin with design goals rooted in criteria of sustainability and informed by a broad awareness of cross-disciplinary and cross-system factors (Chen et al., 2020; Clark et al., 2016).

Systems thinking has been identified as one of five key competencies that are essential for a sustainable future (Wiek et al., 2011) and consequently a vital skill to be acquired by chemists (Matlin et al., 2016). Recent advances in the incorporation of systems thinking in chemistry education (STICE), in particular through the STICE project of the International Union of Pure and Applied Chemistry (Mahaffy et al., 2019a) provided a channel for developing this competence. One of the challenges has been to assist chemists to expand their knowledge of cross-system factors and relevant categories of effects that need to be considered and balanced in the design of products and operation of processes that meet the criteria for sustainability. Visualization tools are of particular value in depicting and exploring system effects, relationships and consequences. Such tools range from relatively simple causal-loop and stock-flow diagrams and concept maps to more complex systemigrams and Object−Process Methodology (Aubrecht et al., 2019).

To provide specific support to enhancing the capacity of chemists to understand and apply knowledge of within-system and cross-system effects, a new visualization tool has recently been developed, the Systems-Oriented Concept Map Extension (SOCME) (Mahaffy et al., 2019b; Aubrecht et al., 2019).· While drawing on many of the features found along the spectrum of available visualization tools, the SOCME is particularly designed to enable sub-system boundaries of interest to be explored and extended for different contexts (Aubrecht et al., 2019) and aspects of complexity (Constable et al., 2019).

The following examples use the SOCME to illustrate interconnections between chemistry and other systems relevant to reducing waste, identifying challenges and opportunities for achieving material circularity through more extensive and more sustainable recovery of matter and value from materials hitherto discarded, and taking account of broader sustainability criteria beyond material circularity.

The three case studies highlight the range and complexity of problems and development of chemistry-based solutions associated with a post-trash approach to the production, use and further handling of (1) the element aluminium – a highly recycled metal, but still requiring new mining and creating a large environmental footprint due to energy consumption and inadequate handling of wastes at all stages; (2) plastics – complex organic materials (mostly synthetic, but also can be produced from bio/renewable sources, often combined with additives to alter performance or appearance) that are poorly recycled, with a substantial environmental footprint; and (3) textiles – very complex materials containing both natural and synthetic components (with high numbers of additives to alter performance or appearance and many chemicals needed for manufacturing), often having low rates of use before being discarded and very low recycling levels. In each case, the material circularity perspective is applied not only to the principle products themselves but also to the by-products and waste, breakdown and end-of-life materials associated with them.

5. Case Study 1: aluminium

5.1. Key facts

The most abundant metallic element in the Earth's crust (c. 8% by mass), aluminium is not found in the native state as free metal but occurs in the form of compounds including alum, feldspars and bauxite (hydrates of alumina, Al_2O_3). With a combination of strength, lightness, resistance to corrosion and good electrical and thermal conductivities, aluminium is the most widely used nonferrous metal. It is also one of the most extensively recycled materials in the world.

The world source of new aluminium is bauxite ore, for which the global mining market was over US$ 12 billion in 2018 and projected (Persistence Market Research, 2019) to have a compound annual growth rate of 6.6% through to 2026.

5.2. Post-trash progress, potential and challenges

The production, use and recycling of aluminium (Habashi, 1995;

Donoghue et al., 2014; Anglo-African Minerals, 2020) are illustrated in the SOCME in Fig. 2 and discussed below, with an emphasis on chemical science challenges to further enhancement of post-trash management.

1.**Extraction:** Crude bauxite ore is a mixture containing aluminium oxide/hydroxide minerals along with compounds of many other elements, including heavy and rare earth metals. The crude ore rock (300 million tonnes per year, globally) is extracted by mechanised strip mining, then crushed and washed before being moved by land or sea for further processing – all of which processes consume energy, usually derived from fossil fuels.

2.**Local Environment:** Exposure and fragmentation of crude bauxite ores during extraction creates dust and channels for leaching soluble materials (some with significant toxicities, such as chromium) into nearby land and water courses, with environmental and health implications for both miners and local communities (Lee et al., 2017).

3.**Alumina purification:** Almost all purified alumina is prepared using the Bayer Process, in which the crushed, washed ore is heated (140–240 °C) under pressure (up to 35 atm) with a solution of sodium hydroxide (produced industrially by the electrolytic chloralkali process (Du et al., 2018). After separation of the solution from solid residues, aluminium hydroxide is precipitated, washed and heated (1100–1200°°C) to provide purified alumina. The required energy is usually derived from fossil fuels.

4.**Non-gaseous by-products:** The residual sodium hydroxide solution is a highly alkaline side-product, mainly containing red iron oxide (up to 60% of the mass), as well as compounds of most of the other co-occurring elements present in the source ore. Over 160 million tonnes of this material, known as 'bauxite tailings/residue' or 'Red Mud', was produced alongside 126 million tonnes of purified alumina in 2018.

5.**Red Mud applications:** Disposal of the large amount of Red Mud has been an ongoing challenge over the last century (Alam et al., 2018), particularly in view of its toxicity (Mayes et al., 2016). Since the 1980s, there has been increasing effort to wash and dry the red sludge, affording a powder that can be used in cement, concrete and other applications (Ujaczki et al., 2018) while enabling recycling of the sodium hydroxide.

6.**Core reaction – aluminium production:** Over 90% of refined alumina goes to the production of aluminium metal, via the Hall–Héroult Process invented in 1886. Purified alumina is dissolved at 950–980 °C in a mixture of molten cryolite (Na_3AlF_6) and calcium fluoride (CaF_2), which is then electrolysed in cells to yield liquid aluminium metal that is run off to be solidified (Kvande and Drabløs, 2014).

7.**Energy sources:** The Hall–Héroult Process is highly energy-intensive (about 15.7 kWh of electricity is required to produce 1 kg of aluminium), with electric power accounting for about 20–40% of the overall cost of aluminium production, depending on smelter location and electricity source. Hydroelectricity is a renewable input where available (but also has an environmental footprint, including from construction and from ecological impacts of dams) and accounts for about half of aluminium production, while carbon-based fuels account for 45%.

8.**Gaseous by-products:** There is also a significant carbon footprint associated with bauxite transport (e.g. Iceland, while lacking bauxite deposits, is a significant aluminium producer using its readily available hydroelectric power) and with the oxidation of carbon electrodes (Equation (1)). During electrolysis, the electrodes release about 13 tonnes of CO_2 per tonne of aluminium produced (Das, 2012) and also create volatile perfluorocarbons such as CF_4 and C_2F_6 with greenhouse gas ratings significantly higher than for CO_2 itself (Gibbs et al., 2002).

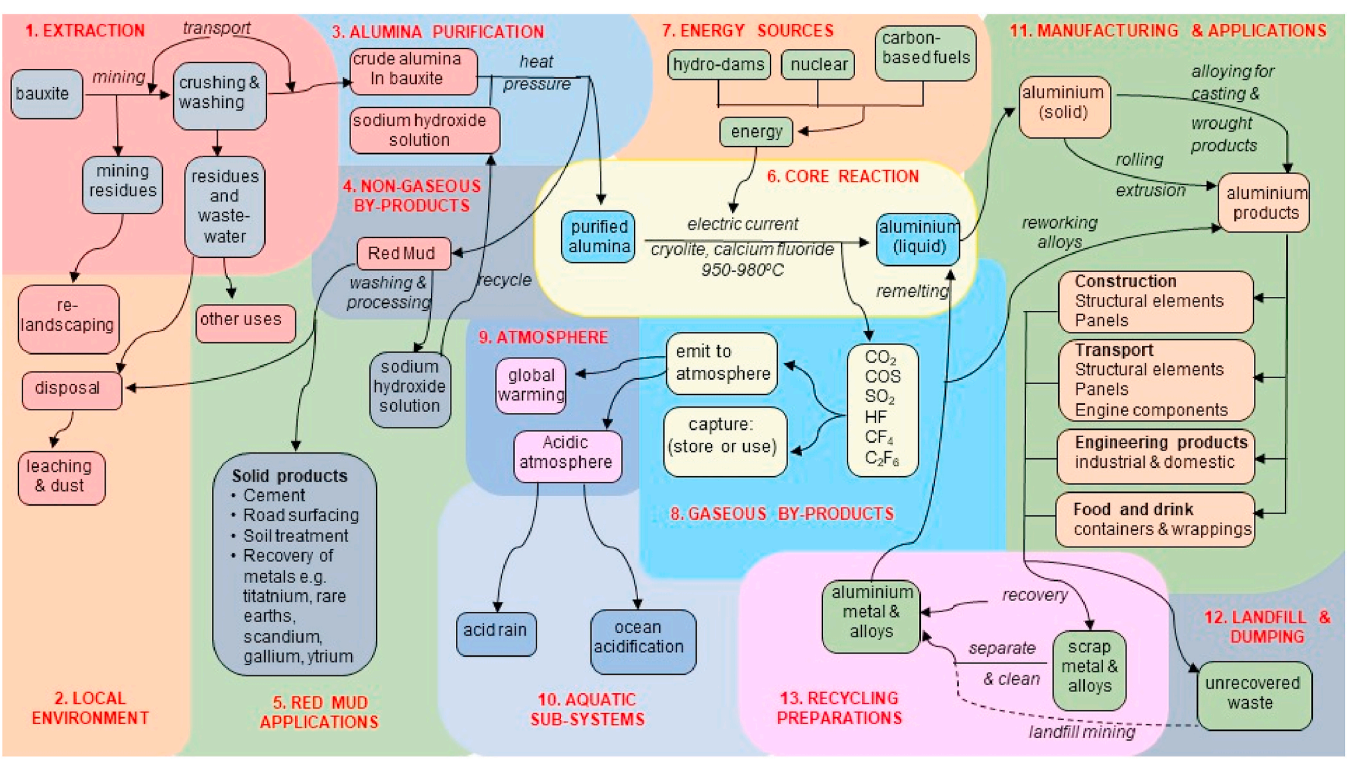

Fig. 2. Systems-Oriented Concept Map Extension for aluminium production, use and recycling. The sub-systems depict (1) Extraction of crude bauxite ore, which has local environmental effects (2) while providing crude alumina (3). This is dissolved in sodium hydroxide solution and re-precipitated to generate purified alumina, but also generates (4) large amounts of waste material (Red Mud) which needs to be disposed of or used elsewhere (5). The core reaction (6) of aluminium production is a highly energy-intensive electrolysis (electricity from diverse sources, 7), which generates numerous gaseous by-products (8) that impact on atmospheric (9) and aquatic (10) systems, as well as providing liquid aluminium for diverse manufacturing applications (11). Comparatively little used aluminium goes to landfill or dumping (11), with most being recovered and reused (13). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Other hazardous by-products of primary aluminium production include hydrogen fluoride (HF) for which the source of fluorine is the electrolyte, and carbonyl sulfide (COS) and sulfur dioxide (SO_2), the source of sulfur being contamination of the carbon anodes during their preparation (Mintsis et al., 2018).

$$2Al_2O_3 + 3C \rightarrow 4\ Al + 3CO_2 \quad (1)$$

9.**Atmosphere; and 10. Aquatic sub-systems:** Globally, the aluminium industry is responsible for around 1% of anthropogenic greenhouse gas emissions, of which around 40% result directly from the aluminium production process itself and 60% indirectly from electricity generation (Nowicki and Gosselin, 2012). Enclosed hoods are increasingly being incorporated on electrolytic cells so that waste gases can be captured and treated (Kalban, 2018), and efforts are being made to introduce inert alternatives to carbon anodes (Editorial, 2018). The gases emitted into the atmosphere contribute to global warming, acid rain and ocean acidification.

11.**Manufacturing and applications:** Aluminium is mostly combined with up to 20% of other elements in alloys (Hirsch et al., 2008) having favourable properties for rolling or extruding into different shapes, or for casting or making wrought metal. Very diverse applications include some where aluminium is layered with other materials such as cardboard (e.g. in drinks containers) and plastics (e.g. in insulations), creating complex, non-recycled materials.

12.**Landfill and dumping:** Relatively little aluminium goes to waste disposal, compared with other industrial products. Nevertheless, there is potential for further capture and recovery of aluminium from its applications, and also for undertaking landfill mining and reclamation (Wagner and Raymond, 2015; Strange, 2020).

13.**Recycling:** Several factors have contributed to relatively high aluminium recycling rates:

- Aluminium is one of the most cost-effective metals to recycle: remelting uses only 5% of the energy required for primary production.
- Recycling can be accomplished very rapidly (Micu, 2019).
- Recycling of aluminium was given major impetus by its shortage in World War 2 and by public pressure for recycling aluminium cans when they began to be widely used in the mid-20th Century.

Methods for recapture and recycling of aluminium depend on the nature of the products concerned. 'Aluminium cans' are usually made from aluminium alloys, typically containing 92.5%–97% aluminium, as well as magnesium, manganese, chromium and trace amounts of iron, silicon and copper. About 200 billion aluminium cans per year are used globally, and in Europe the overall recycling rate reached a record high of 75% in 2017 making aluminium drinks cans the Earth's most recycled packaging product (Bunting, 2019). Since the compositions of aluminium alloys used in different applications vary widely, comprehensive recycling requires identification and sorting, where necessary followed by appropriate alloying with fresh aluminium or other metals for further applications.

5.3. Summing up

It was assessed in a 2009 report (Global Aluminium Recycling Committee, 2009) that, of an estimated total of over 800 million tonnes of aluminium produced globally since commercial manufacture began in the 1880s, about 75% is still in productive use and aluminium is regarded as a leading example of the circular economy (Geng et al., 2019). However, the Case Study points to areas at every stage from extraction to re-use where sustainability improvements can be made, greater material circularity achieved and greater economy and sustainability of energy generation and use accomplished, concerning not just the conservation of aluminium itself as a useful resource but also considerations of the inputs, outputs and fates of many other associated materials. Particularly important will be improvements to the extraction and purification of bauxite (especially regarding the production and further use of Red Mud), reduction in the generation of gaseous by-products in the electrolysis of bauxite and capture and sustainable use or disposal of those that cannot be avoided, and improvements to the processes for recovery, sorting and re-use of aluminium products.

6. Case Study 2: plastics

6.1. Key facts

Plastics comprise a wide range of polymeric organic compounds, often including complex mixtures within the polymer itself (co-polymers) and with other, smaller molecules (additives), that can be moulded into solid objects.

The first commercialised synthetic plastic, Bakelite, produced in 1907, found many applications in industrial and domestic appliances due to its heat resistance and lack of electrical conductivity. Rapid growth in global production of plastics began in the 1950s with the large-scale manufacture of a wide range of polymers based on hydrocarbon, ester and amide linkages, increasing from 2 million tonnes in 1950 to over 420 million tonnes in 2017. China has become the largest producer, accounting for nearly 30% of the global total. Half the applications are single use and then thrown away, generating a growing waste stream that outstrips declining landfill space and enters the oceans (Jambeck et al., 2015). Until quite recently (Beckman, 2018), "polymer product designers have typically not considered what will happen after the end of their product's initial lifetime".

Relatively little plastic is recycled and consequently plastics have been a rapidly growing segment of MSW (USEPA, 2019). In the USA, which generates about 100 kg of plastic waste per person per year, the overall plastic recycling rate in 2015 was 9%. Having handled nearly half of the world's recyclable waste for a quarter century, China's ending of importation of waste materials, including plastics, from January 2018 has major implication for waste management in a number of countries, with more plastics likely to enter landfills and incinerators or be discarded in the environment (Brooks et al., 2018).

6.2. Post-trash progress, potential and challenges

The production, use and fates of plastics, including recycling, are illustrated in the SOCME in Fig. 3 and discussed below.

1.**Non-renewable sources:** Most primary feedstocks for plastics production are non-renewable, with 99% of monomers for polymerization being derived from fossil fuels. About 4% of annual total use of oil and gas worldwide is for plastics production. By far the largest commercial chemical product by volume globally, ethene (ethylene) is the most important monomer, with around 150 million tonnes/year currently produced, of which 60% is used in polyethylene production.

2.**Renewable sources:** There is a small but growing interest in the use of renewable feedstocks from plant and microbial sources, through the breakdown of natural polymers like cellulose and lignin and further chemical or biotechnological processing (Mohsenzadeh et al., 2017). In 2018, global bioplastic production reached 2.1 million tonnes (British Plastics Federation, 2019), around 0.5% of the total plastic production that year.

3.**Plastics:** Alkenes are used to synthesise a number of polyalkenes and ethene is also converted into vinyl chloride, the feedstock for polyvinyl chloride. (PVC). The alkenes and also aromatic hydrocarbon compounds are sources of organic acids, alcohols and amines that can be reacted to form polymeric esters (e.g. poly (ethylene terephthalate) or PET) and amides.

Thermoplastics (e.g. acrylic, PET, PVC and Teflon) become plastic on heating and harden on cooling, and are able to repeat these processes, allowing them to be shaped via extrusion and injection moulding and conferring a high re-usability potential. By contrast, thermosetting

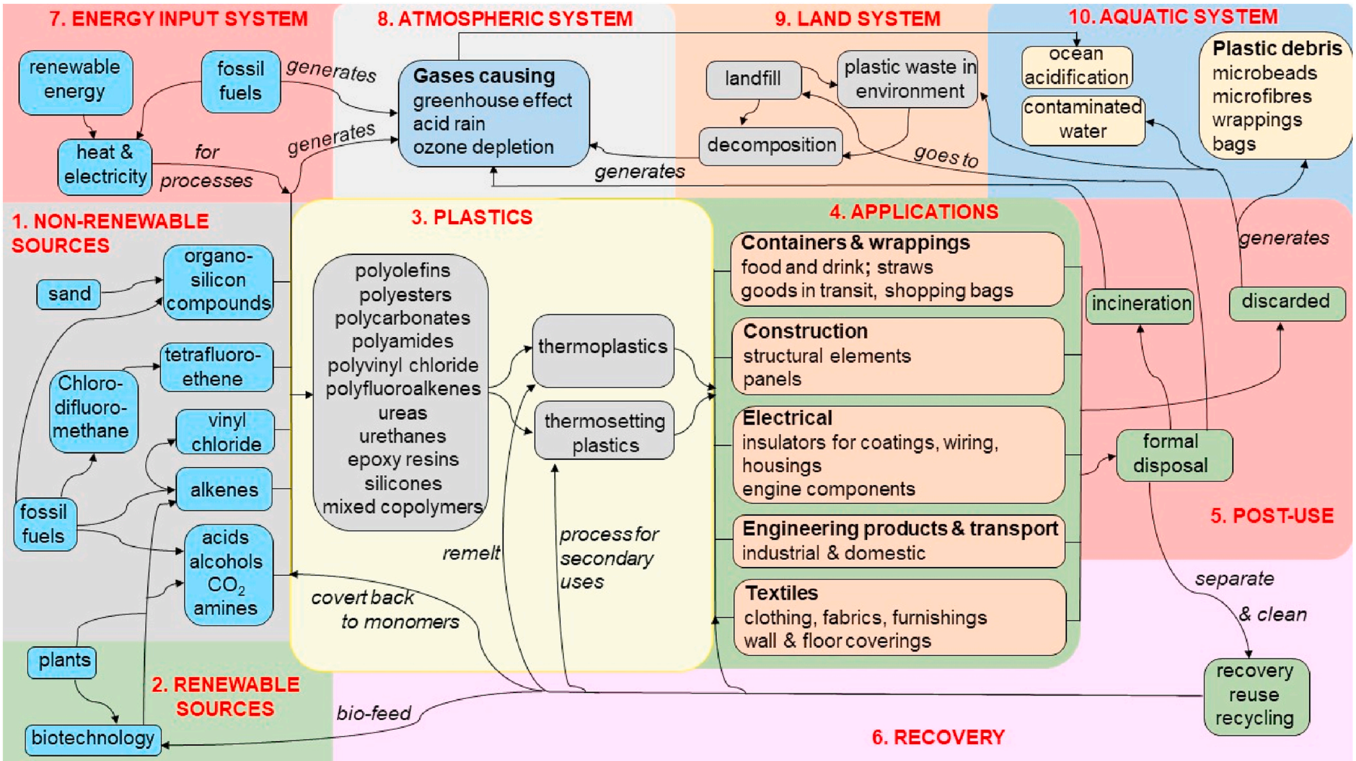

Fig. 3. Systems-oriented concept map extension for production, use and recycling of plastics. Monomer sources for plastics (1) are almost entirely non-renewable, although there is potential for use of renewable bio-feedstocks (2). Energy sources for monomer and polymer production are also mainly non-renewable (7). Thermoplastic and thermosetting varieties of polymers (3) find diverse applications (4). Post-use (5), both formal disposal by incineration or landfilling and informal discarding have adverse impacts on the environment (8–10). Relatively little plastic is recovered (6) for re-use or recycling into new applications or breakdown or bio-conversion back to monomer feedstocks.

plastics (e.g. Bakelite, epoxy resins, polyurethane, silicones) are irreversibly hardened by curing with heat, radiation or a catalyst, which causes permanent cross-links between the polymer chains, so that the material usually cannot be re-melted once formed. Chemical recycling of traditional thermosetting plastics has been extremely difficult, but new polymer designs with greater chemical recycling potential are now beginning to be explored (Post et al., 2019).

4.**Applications:** Thermoplastics uses include packaging, pipes, ropes, casings, insulation, materials in construction of buildings and vehicles, furniture and components of many industrial and household goods. Thermosetting plastics are typically harder and stronger than thermoplastics, more resistant to chemical degradation and impact damage and better suited to high-temperature applications. They find a wide range of uses, including in protective coatings, insulating materials and construction in civil engineering and domestic settings.

5.**Post-use; and 6. Recovery:** At the end of their initial intended use, plastics may be disposed of formally, or informally discarded by abandonment in the environment. Formal disposal includes incineration, landfill (accounting for about 12 percent of the present total of all MSW) (Ellen MacArthur Foundation, 2016) and a limited amount of primary recycling, with some recycled thermoplastics being returned to use as or remade into the original products (e.g. PET bottles), or secondary recycling by re-melting and incorporation in paints, clothing, car interiors and headphones.

Compared with aluminium, the practical number of recycling of plastics is more limited as they gradually degrade in chemical structure (e.g. due to effects of heat and sunlight) and physical properties, and also contain specific additives from their original production, so that their applications move more rapidly down the value chain and waste hierarchy over time. In principle, this can be offset by chemical reactions leading to decomposition or depolymerization processes that regenerate monomers for new plastics production, but such approaches have yet to be applied on a large scale and the additional material and energy requirements and overall sustainability are as yet unclear (Jehanno et al., 2019). While thermosetting plastics cannot be reshaped by reheating, they can be crushed to produce small pieces used in manufacturing, for example, aggregates with concrete or wood, or carpet underlays, but the potential (if any) for further recycling of these latter materials has yet to be established and energy inputs for all steps, including sorting and separating, require consideration.

Increasing attention has turned to the use of biodegradable plastics, especially for single-use applications such as short-term food containers and packaging. Some bio-plastics are designed to be readily depolymerised back to the monomer. For example, poly (lactic acid) can be hydrolysed back to lactic acid, which can be purified and used to make virgin polymer again, but with implications for the consumption of energy and reagents in the process (Floreon, 2014).

7.**Energy input system; and 8–10. Atmospheric, land and aquatic systems:** In addition to consuming fossilised carbon sources as the chemical feedstock, polymer processing is an energy-intensive industry, with the synthesis, reaction and plasticisation processes using electric power for thermal energy (Khripko et al., 2016). The energy is mostly derived from fossil fuels, adding to generation of gasses causing greenhouse effects and acid rain (e.g. CO_2) as well as stratospheric ozone depletion (e.g. halogenated hydrocarbons). In addition, the methods of disposal of plastics (Fig. 3, sub-system 5) can also be sources of greenhouse gasses, including from incineration and from (photo)chemical or biological degradation in the environment. Despite their relative chemical inertness, the most commonly used plastics such as polyethylene produce two greenhouse gases, methane and ethene, when exposed to ambient solar radiation (Royer et al., 2018).

Plastics entering the planet's aquatic system through deliberate discharge or negligent disposal are now recognised as a severe ecological threat. Plastic items such as containers and wrappings are found in the digestive tracts of larger aquatic species, while microfibres (e.g. from synthetic clothing) and microbeads (e.g. from physical abrasion of large plastic items and from toiletries and household products flushed to waste) are ingested even by small aquatic organisms.

6.3. Summing up

Due to the sources, high usage, poor recycling rates and large environmental footprint of plastics, they have emerged as a major threat to sustainability. Application of the chemical sciences is fundamental to improving this picture and enhance material circularity, including reducing the dependence on fossil fuels as the primary source through development of processes for the transformation of bio-based materials into feedstocks for polymerization and invention of new polymerization processes and polymer products that are more readily recyclable and/or biodegradable, as well as of new catalysts and processes to facilitate the breakdown and re-use of polymers as valuable chemical feedstocks. The potential for such improvements to strengthen loops of reuse, recycling and renewal of materials involved in plastics has been emphasised, as well as the attendant critical factors of design for sustainability and associated changes in economic, legal and social dimensions to create an environment that drives an overall change in approach to plastics (Clark et al., 2016).

7. Case Study 3: textiles

7.1. Key facts

Fibres from natural sources (e.g. plants, animals) or synthetic organic polymers (e.g. polyesters, polyamides, modified cellulose) are the major building blocks of textiles such as cloth, upholstered furnishing in houses and cars, bags, table cloths, bed linen and carpets. The global production (Textile Network, 2019) of fibres rose 50% from 74 million tonnes in 2008 to 111 million tonnes in 2018. Greenhouse gas emissions from textiles production totalled 1.2 billion tonnes of CO_2 equivalent in 2015, more than those of all international flights and maritime shipping combined (Ellen MacArthur Foundation, 2017c). Cotton is the by far most important natural textile fibre (others include wool and animal hair, flax and silk), with global production of 26.1 million tonnes in 2018, corresponding to more than 81% of the natural fibres and about 23% of natural and synthetic fibres altogether.

Textiles are usually complex mixtures. The fibres themselves may be blends of natural and synthetic materials (which are often themselves mixtures) and the fibres or the composite textile may be treated with a broad range of chemicals to modify characteristics such as colour, water resistance, elasticity, cleaning properties and resistance to wear or shrink. Only a very minor share of textiles is recycled, and there is often a decrease in quality due to fibre ageing and the presence of the additives, which reduce value and consign the textile to lower levels of the waste hierarchy.

7.2. Post-trash progress, potential and challenges

Fig. 4 presents the diversity of processes, along the life stages of

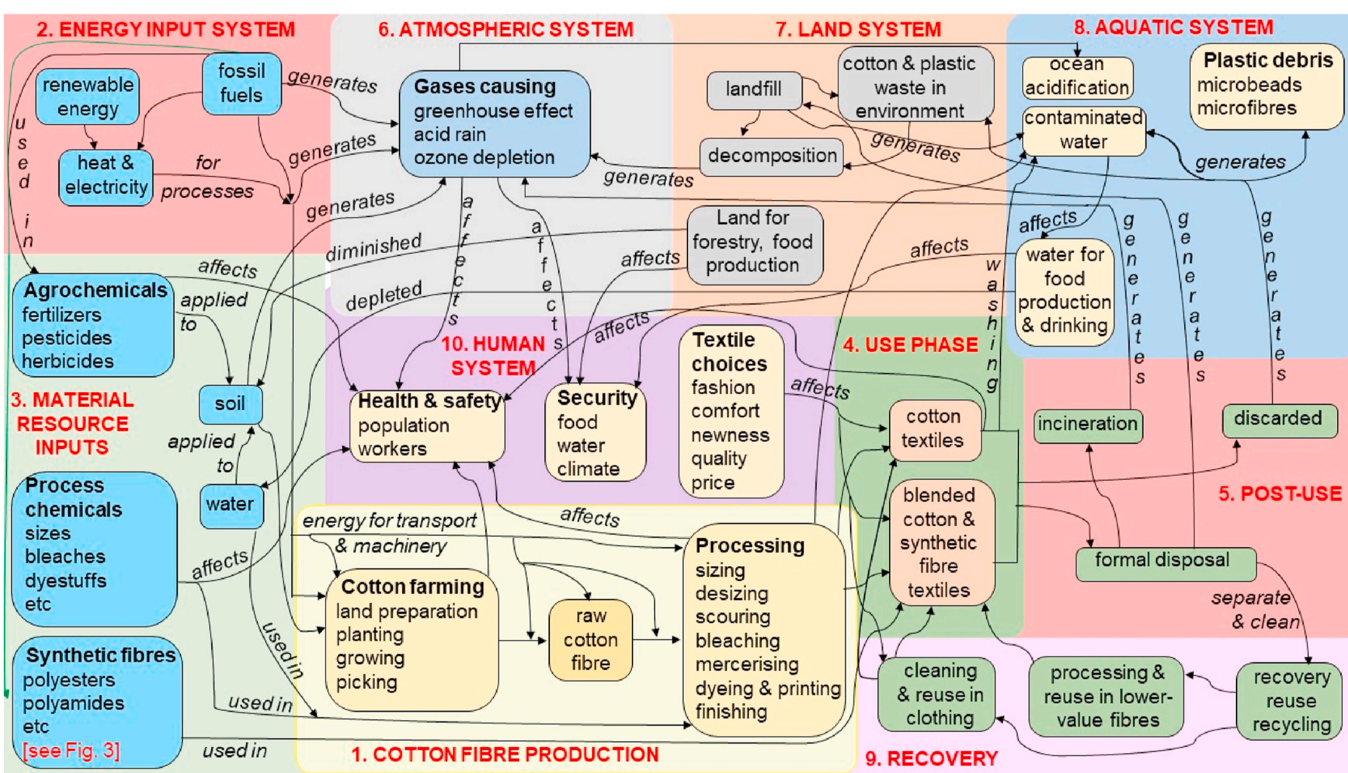

Fig. 4. Systems-oriented concept map extension for production, use and recycling of textiles. Cotton fibre production (1) requires major inputs of energy (2) and agrochemicals (3) for cotton growing, while synthetic fibre production (3) consumes fossil fuels (see also Fig. 3). Further energy is required in the processing of fibres into textiles and finished goods (4) and for cleaning during the use phase (4), which also consumes cleaning agents and leads to release of fibre additives, cleaning compounds and fibre fragments into the environment, with consequences for the atmospheric, land and aqueous environments (6–8). Post-use (5), most textiles are consigned to incineration or landfill, with further environmental impacts (6–8), while relatively little goes to recovery (9) and further applications. Textile production and use has many implications for human health, safety and security, while choices people make about the textiles they use have many implications for the entire system (10).

textiles. Because of the presence of complex additives, textiles made from both natural and synthetic fibres are active sources of environmental pollutants throughout their period of manufacture and intended use, as well as presenting major challenges for recycling and avoidance of waste and environmental contamination subsequently. For synthetic and blended fibres, the waste challenges associated with the plastic components (Case Study 2) apply, compounded by the additional presence of the modifying additives, as well as consequences of fossil fuel consumption such as those illustrated for aluminium (Case Study 1) and plastics.

The SOCME (Fig. 4) depicts the complex natures of textile sources and materials, the treatments they undergo to prepare them for diverse applications and their subsequent post-use fates.

1. Cotton fibre production; 2. Energy inputs; and 3. Material resource inputs: The largest producers of cotton are China, India and the USA (respectively 6.5, 6.4 and 3.5 million tonnes/year). Cotton farming has a substantial environmental footprint, accounting for about 16% of global insecticide use and 3% of the world's irrigation water, with 3000–7000 L of water needed to produce one kg of cotton lint from which cotton fibres are spun (FAO, 2015). Energy inputs to cotton production (mostly oil-based fuels) are used to operate machinery for ploughing, planting, irrigation, fertilizer application, crop spraying, harvesting and for materials and labour transport (Pishgar-Komleh et al., 2012). Globally, cotton production generates emissions of around 220 million tonnes of CO_2 equivalent, or about 0.8% of the global emission total, while consuming about 4% of the world's nitrogen-based fertilisers (The Soil Association, 2015). Cotton yarn and cotton cloth manufacturing also produce CO_2 and wastewater.

Synthetic fibres for textiles include polyesters. PET, the world's most commonly used fibre, overtook cotton use in 2002 and, with other synthetic fibres, makes up more than 65% of fibres used in the textile and apparel industry. Virtually all synthetic organic fibres are made from mineral oil (Fig. 3) and in 2015 this amounted to around 1% of global oil production. Compared to cotton, polyester production has a lower water usage and produces less wastewater which, however, can contain antimony, cobalt, manganese salts, sodium bromide and titanium dioxide and is often released without treatment (Common Objective, 2019). The energy required to produce polyester for clothing resulted in emission of 282 million tonnes of CO_2 in 2015.

The production and use of all fibres, whether natural or synthetic, entails numerous related substances, material flows and environmental issues along the fibre's life cycle. Estimates of the number of different chemicals used in textile production range between 1900 and more than 8,000, with about 5% being considered to be of potential risk to the environment and including at least 165 substances classified as carcinogenic, mutagenic, sensitising or toxic to the reproductive system (KEMI, 2014). Chemicals added to textiles include dyes, oil and water repellents, anti-stain, anti-wrinkle and anti-shrinking agents, flame-retardants, plasticisers, biocidal substances, stabilisers and softeners for surface feel and other effects. Consequently, each fibre and textile has its own chemical fingerprint (Keβler and Kümmerer, 2020).

4. **Use phase; and 5. Post-use:** About 80–100 billion pieces of clothing are produced each year and 'fast fashion' is increasingly popular in many countries, with clothes being bought cheaply, worn very few times and discarded. Of the major proportion of discarded clothing consigned to waste disposal, roughly 70% goes to landfill and 30% is incinerated. Of the clothing initially designated for sorting/recycling, roughly half is recycled and 40% is re-used as second-hand clothing, but the remaining 10% ends up in the waste stream (Kerr and Landry, 2017). Recycling of non-clothing household textiles such as mattresses, carpets and household linens, is undertaken in some countries (Wrap, 2020).
6. **Atmospheric; 7. Land; and 8. Aquatic systems:** Environmental implications of textile production, use and disposal or recycling include the effects of cotton growing on land and water use, impacts of chemicals consumed, whether combusted for energy or applied at the different stages of growing, processing and finishing, or the results of washing (generating contaminated wastewater and microplastic fibres and beads), incineration or environmental decomposition. In addition, the use of synthetic fibres and of metal threads and embellishments implicates environmental impacts of plastics and metals, as discussed in Case Studies 1 and 2.
9. **Recovery:** Up to 95% of the textiles that are landfilled each year could be reused or recycled[68]. A 2018 review (Sandin and Peters, 2018) provided a classification of options for textile reuse and recycling, confirming the relative greater environmental benefits of the former, but also highlighting many gaps in knowledge that require further research. However, a significant factor is the quality of the recycled materials, since 90% of the chemicals that were initially introduced during manufacturing are still present in post-consumer textiles (Nimkar, 2018). Recovery of both natural and synthetic fibres and the depolymerization of polymers to reusable monomers are areas of growing interest (Notman, 2020) (see Case Study 2).

About 5 million tonnes per year of dyes, pigments and finishing chemicals are used in textiles (Nimkar, 2018). They pose both recycling and environmental challenges, complicating the sorting of post-consumer clothing for fibre recovery and recycling, while leaching of additives and their soluble degradation products from waste sites contaminates land and water (Bomgardner, 2018).

10. **Human system:** Textile production has many impacts on human beings, including those engaged in farming, processing and manufacturing fibres and retailing finished textiles, who may be exposed to unhealthy and exploitative working conditions (Menke, 2017) or lack environmental justice (USEPA, 2020). The wider population is also exposed to many of the chemicals employed in production, present in the finished products used and generated during use and disposal – as well as to indirect effects via the environmental impacts associated with textiles, including planetary impacts on the security of food, water and climate.

People's preferences in apparel and furnishing fabrics are strongly influenced by the fashion industry and local culture as well as by comfort, quality and affordability. Personal attitudes are also central to whether clothing is valued for durability or there is a preference for frequent discard and replacement and whether reused (second-hand) clothing or recycled materials are accepted.

7.3. Summing up

The increased understanding of the environmental impact of plastics in recent years contrasts with the generally low level of public and political awareness of the major challenges to the environment and to sustainability more broadly that are presented by textiles. Yet, plastics comprise more than 50% of the textile materials currently in use and even for the natural fibres such as cotton there is a substantial environmental footprint related to cultivation, manufacturing, transport and disposal – in contrast to the widespread assumption that natural fibres must be environmentally friendly. With high rates of discard of clothing in good condition and low rates of recycling, there is a perspective (Boström and Micheletti, 2016) that "clothing and textile production is one of the most polluting industries in the world".

Potential improvements in material circularity include the sustainable sourcing, synthesis and disposal/recycling of plastics used in textile manufacture (see Case Study 2), more sustainable production of natural fibres through better agrochemicals design and use, development of new fibres/blends with extended lifetimes, improved design for separation and alternative fibre additives that provide desired functionality with improved safety and recyclability, and new processes for recovery of textile components and their re-use in high-value applications. In addition to these material circularity-related factors, more attention needs to be given to the comprehensive consideration of water use, contamination and clean-up at all stages from primary sources (agriculture, petrochemicals, bio-production) to use, re-use and recycling, as well as to the qualitative and quantitative nature of energy inputs and waste outputs associated with all these stages.

A circular economy approach to textiles (Ellen MacArthur Foundation, 2017b; To et al., 2019) requires achieving four ambitions, based on systems thinking and system-level changes: (1) phase out substances of concern and microfibre release; (2) increase clothing utilisation; (3) radically improve both lifetime and recyclability; and (4) make effective use of resources and move to renewable inputs. Necessary areas of action include: establishing a robust, open evidence base regarding the composition of textiles beyond the main fibres, and system impacts, to aid stakeholders in defining actions required to change the system; innovation; policy; transparency; marketing; and getting decision-makers to appreciate the advantages of circular models.

8. Conclusion

Securing the sustainability of the planetary environment will not be achieved without addressing the challenges of (1) reducing all forms of waste emitted, whether in solid, liquid or gas forms and whether originating from the materials manipulated to source, transform, use and recycle or dispose of products and by-products or from the energy required to undertake these steps; (2) maximising material circularity as much as is practical; and (3) better managing all waste not currently recyclable to ensure conservation of potential future resources and minimum environmental harm.

There can be no single or simple approach: the problems of minimising waste (whether in solid, liquid or gaseous forms and whether associated with product creation, use, recycling or disposal of materials or the associated generation and use of energy) and achieving material circularity sustainably are different for each material and each process considered. However, they share some general principles. Solutions to the problem of sustainability of production and use of metals, plastics and textiles will necessarily be complex and multi-faceted, given the range of social, economic and technological factors that intertwine in each global industry. These have to be understood and addressed from the very beginning of the life cycle of products, aiming first to avoid waste, in terms of both generation and by efficient recapture and reuse of matter at all stages, and second to achieve significant reduction of chemicals and materials used, both in volume and diversity as well as in the complexity of products. Product design (Zimmerman et al., 2020) is key to enabling increasing savings of physical and energy-related resources, reducing flows and lowering environmental impact. Design at levels from atomic/molecular to building blocks and products enables better separation as an important prerequisite for reuse and recycling. The chemical sciences play enabling roles at many stages, including innovation in chemical processes and products as one of the essential inputs. To make optimum contributions, the discipline needs to be oriented and adapted for sustainability (Kümmerer et al., 2020) and substantial further research, involving chemistry in tandem with many other disciplines, will be necessary ((Keβler and Kümmerer, 2020; Sandin and Peters, 2018).

In every case, tackling the challenges requires a combination of scientific/technical capacity to which the chemical sciences can contribute, economic viability and political and social support. The increasing attention that has been given to recycling of aluminium cans and reduction in use of plastic items such as single-use bags, with social pressure being accompanied by political action and economic incentives, demonstrates that change is possible. This experience urgently needs to be applied in other areas, as exemplified by textiles.

Achieving a post-trash age necessitates inputs from the chemical sciences along three channels (Matlin et al., 2019) of simultaneous and interactive action, aiming to (1) clean up: dealing with historic waste on land and in the planet's atmospheric and aquatic systems; (2) catch up: dealing with outputs/waste from materials currently in use and in production; and (3) smarten up: progressively improving design, planning and management based on sustainability criteria and the overall objective of maximum practical material circularity. This means that chemists must work with a wide range of other actors, across other fields of science and technology, with industry and with civil society and policy-makers.

Engagements between those undertaking research and design with those involved in industrial production, regulation and taxation and with opinion formers and fashion and trend creators in society must therefore become an increasingly common component of the skill-set of chemists. The trends for increasing attention to sustainable chemistry and acquisition by chemists of skills in systems thinking supported by tools such as SOCME and LCA are important signposts along this pathway, needing further encouragement by academic institutions, research funders and industry (Funk and Ash, 2020). Governments must further build and reinforce the legislative and economic frameworks that enable, drive and sustain these developments, as exemplified by the evolving position of the European Union in programmes on waste and circularity (European Commission, 2015 & 2020b). Where appropriate, there may be further development and application of instruments such as eco-taxes (European Environment Agency, 2016) and the Green Deal (European Commission, 2019), as well as consideration of innovation incentives such as prolonging patent lifetime and fast-tracking registration of new chemicals and products.

Author contributions

S.A.M. coordinated the writing of this article. All authors contributed substantially to the conceptualization of the topic and the writing of the article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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