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From rags to riches: the role of the chemical sciences in transforming waste into valuable products

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The growing volume and complexity of anthropogenic waste presents a serious risk to ecosystems and human health.[1] In addition to the two billion tonnes of solid municipal waste produced globally each year, human activities generate significant amounts of waste as by-products from industrial and agricultural processes, including greenhouse gases such as carbon dioxide (CO_2).[1,2] Our current 'linear' economy, in which products are used and then disposed of, is unsustainable, generating overwhelming quantities of waste and depleting natural resources faster than they can be replenished.[3]

To reduce waste, a fundamental change in our economic model is needed. The 'circular economy' seeks to break the link between economic activity and the consumption of finite resources, keeping products and materials in use for as long as possible in closed-loop systems.[3] The chemical sciences have a central role to play in facilitating the shift to a circular economy, both *via* the development of efficient recycling processes to convert waste into valuable chemicals, and *via* the creation of more sustainable materials that are designed with their eventual disposal in mind.[4,5]

This essay focuses on three prevalent forms of waste in modern society: CO_2 waste, plastic waste, and waste from electrical and electronic equipment (WEEE).[6–8] A selection of innovative methods, grounded in the chemical sciences, for creating value from these three waste streams are discussed, with an evaluation of their scale-up potential and industrial viability.

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Value from waste carbon dioxide

Carbon Capture and Utilisation (CCU) is a method of reducing emissions while also promoting circularity, as waste CO_2 is captured prior to release into the atmosphere and then transformed into useful products. While the inherent stability of the CO_2 molecule poses a challenge, several chemical methods for its transformation have been developed.[6,9,10]

CO_2 conversion to methanol is of particular interest due to its use as a starting material for the production of polymers, resins and coatings.[11] Carbon Recycling International, based in Grindavik (Iceland), operates one of the largest

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CO_2-to-methanol conversion plants, with over 200 000 tonnes per year of methanol production capacity.[12] Their patented process involves reaction of hydrogen, generated from renewable energy *via* electrolysis, and CO_2, extracted and purified from the flue gases of a nearby geothermal power plant, over a heterogeneous catalyst to form methanol and water.[13] In addition to utilising CO_2, this process shows benefits over the conventional production of methanol from syngas (CO and H_2), as it involves milder conditions and easier product purification.[14]

Formic acid production from CO_2 has also been explored, with applications as a food preservative and as a building block for further chemical synthesis.[11] An electrochemical method of CO_2 conversion from flue gas to formic acid, facilitated by amines, has been demonstrated at the pilot plant scale (10 kg per day), producing high purity formic acid.[15] Life-cycle assessments and technoeconomic analyses reveal that this process reduces the global warming impact and production cost by 42% and 37% respectively, compared with conventional formic acid production.

As a third example, CO_2 conversion to materials (polymers) is possible through the copolymerisation reaction of epoxides and CO_2, to produce polycarbonates.[16] This reaction is compatible with a range of different epoxides, including those that are bioderived, and the resulting polymers are compatible with chemical and mechanical recycling.[4,17] The utilisation potential of CO_2 for the production of polymers is projected to be between 10 and 50 million metric tonnes per year by 2050, and production at the kiloton scale is being developed by companies such as Saudi Aramco, Covestro and Econic Technologies.[9,18–21]

With any CO_2 conversion process, it is important that the CO_2 offsets, associated with its use as a starting material, outweigh any potential CO_2 emissions from the energy and resource requirements necessary for its chemical transformation. Harsh operating conditions, expensive catalyst synthesis and lengthy product purification increase CO_2 emissions and should be avoided. Compatibility with contaminants in unpurified CO_2 streams from industrial flue gas is also desirable, reducing the need for extra extraction and purification steps, and this should be a focus of future research efforts.

Value from waste plastic

Plastics, as lightweight, durable and chemically inert materials, find applications in many sectors including construction, aerospace, furniture and packaging.[22] Global plastics production is rapidly increasing, now rising to 400 million tonnes per year, but the chemical inertness and durability of plastic products complicates their end-of-life treatment.[23] Of all the plastic waste generated, only a small amount is recycled (<10%) with the rest incinerated, landfilled or released into the environment. Therefore, efficient methods of plastics recycling are vital to 'close the loop', protecting our environment and precious natural resources. Chemical recycling of plastic (polymer) waste, to produce valuable monomeric or oligomeric compounds, is a promising approach as the products can be used as building blocks for production of materials with virgin-like properties.

One method of chemical recycling is *via* hydrogenolysis, in which polymer chains are broken down into liquid and gas-phase hydrocarbons under high pressures of hydrogen, typically in the presence of a heterogeneous catalyst.[7] A recent study finds a catalyst incorporating ruthenium nanoparticles supported on titania (Ru/TiO_2) breaks down commercial polyethene samples (plastic bottle caps) to liquid and gas phase hydrocarbons.[24] Ru/CeO_2 and Pt/CeO_2 catalysts successfully depolymerise commercial polyamides (such as nylon fishing nets), including polyamide blends and composites.[25] While initial investigations are promising, the requirement for high hydrogen pressures (20–50 bar) and the need to source ruthenium, an expensive and rare metal, for catalyst production hinder scalability of this process in its current form.

Emerging methods of chemical recycling include photocatalysis, where light is used to initiate redox reactions to generate useful chemical products.[7] A two-step process from commercial plastics (including single-use bags and disposable food containers) to acetic acid has been reported using a Nb_2O_5 photocatalyst.[26] Chemical recycling *via* hydrolysis is also possible, which can be performed under mild conditions and handle highly contaminated waste streams. A recent report converts commercial polyethylene terephthalate (PET) waste back to the constituent monomers *via* hydrolysis, although use of large quantities of solvent at scale leads to a high energy consumption, and significant cost associated with separation of the desired product.[27]

While development of chemical methods for plastics recycling is important, other sectors have a crucial role to play in establishing a circular plastics industry. For example, governments should impose bans, eliminating plastic products that we do not need. Furthermore, companies should redesign products with future sustainability in mind, incorporating renewably sourced and degradable materials, and be obliged to take some ownership of the waste associated with their products.

Value from waste electronic and electrical equipment

Rapid technological developments over recent decades have fuelled an increase in the quantity of waste electronic and electrical equipment (WEEE), with 62 billion kilograms generated globally in 2022, only a small proportion of which (22.3%) was documented as recycled.[28] However, WEEE is a valuable source of precious metals (such as palladium, platinum, gold and silver) which could be extracted and re-used, reducing the need for emissions-intensive extraction from the ground.[8,29] However, novel chemical methods are needed to increase the recovery efficiency of these precious metals.

Pyrometallurgy, used industrially, involves heating pre-treated WEEE to high temperatures to recover metals (such as copper) while impurities are removed as slag.[8] However, an emerging and more eco-friendly alternative is 'hydrometallurgy', referring to the recovery of metals from pre-treated WEEE using controlled chemical reactions.

Hydrometallurgy involves two distinct steps: chemical leaching of the metals and extraction of the metals from the leachate. Leaching of metals can be achieved using acids, or ligands such as cyanide (in the case of gold), but sometimes more corrosive reagents are necessary (such as hydrochloric acid or aqua regia).[30] Solvent extraction and ion exchange processes are commonly used to extract metals from the leachate. However, hydrometallurgy generates large amounts of wastewater that must be carefully managed, and the need for expensive, anti-corrosive equipment currently limits industrial application. The search for less corrosive, more eco-friendly leaching agents is a topic of current research.[8]

Conclusions

The chemical sciences have a crucial role to play, as the source of many innovative solutions for the recycling and valorisation of three diverse waste streams (CO_2, plastics and WEEE). However, achieving a fully circular economy demands both innovative scientific solutions and supportive political and economic policies.

Governments and policy makers must continue to fund research and development, whilst establishing regulations to limit waste generation and provide companies with financial incentives for recycling. Moreover, public education and engagement is essential to build a social acceptance of environmental issues and encourage governments and political parties to adopt 'green' policies. It is also imperative that chemists and research funders think of the 'bigger picture', using life cycle and technoeconomic assessments to inform on the most promising and economically viable research directions.

The scale of the challenge ahead is huge, but through combining the chemical sciences, economics and favourable policies and regulation, then a sustainable future is achievable for us and future generations to come.

Conflicts of interest

There are no conflicts to declare.

Data availability

There is no additional data associated with this article.

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