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International Organization for Chemical Sciences in Development

ROYAL SOCIETY OF CHEMISTRY

YOUNG VOICES IN THE CHEMICAL SCIENCES FOR SUSTAINABILITY 2025

Winners and Finalists in the IOCD Essay Competition sponsored by the Royal Society of Chemistry

From waste to wealth: how chemical sciences can sustainably transform waste into valuable products

Editors: Stephen A. Matlin, Federico Rosei, Philippe Lambin and Lei Jin

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Introduction

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Background

IOCD promotes the pursuit and application of the chemical sciences for sustainable, equitable human development and economic growth, working to reposition chemistry as a science for the benefit of society and promote the role of the chemical sciences in sustainable development. IOCD's action groups cover a range of strategically chosen activities to advance this mission (Box 1).

Box 1 IOCD action groups[1]

Materials for Energy Conversion, Saving and Storage (MATECSS)[2] is led by IOCD's Executive Director Federico Rosei. The group seeks to facilitate technology transfer by connecting experts from around the world with local scientists, engineers and students in low-and middle-income countries, and to foster development of low cost, adaptive technologies based on energy materials appropriate for local-scale energy systems and that use local resources.

Chemists for Sustainability (C4S)[3] is an international group of chemists providing advocacy and think-tank roles through written articles, lectures at various fora and web materials,[4] building the case for chemistry's central contributions to sustainable development.

Green and Sustainable Electronics (GSE) is a Working Group led by Teressa Cechi in Fermo, Italy, in collaboration with Clara Santato who holds the UNESCO Chair in GSE at Polytechnique Montreal in Canada.[5] The group focuses on the growing environmental burden of waste electronic and electrical equipment, collaborates with Sub-Saharan countries that have been considered e-waste dumping sites, for recovery, upcycling efforts and eco-design.

The **Chemistry Education** Working Group makes the case for reorientation of the curriculum to enable it to better serve the needs of society to understand and tackle the unfolding global crises of the 21st century.[6] In collaboration with the International Union of Pure and Applied Chemistry, IOCD has contributed to the leadership of global projects to help embed systems thinking in chemistry education[7] and to engage with chemical industry on systems thinking and sustainability.[8]

As part of its strategy, IOCD seeks to stimulate young people to develop their roles in reshaping chemistry as a core sustainability science – including through encouraging them to write about the subject. In 2023, IOCD launched an annual Essay Competition, ***Young Voices in the Chemical Sciences for Sustainability***.[9]

The competition, organized and managed by IOCD, to highlight the roles of the chemical sciences in promoting sustainability and to encourage young people (aged under 35 on the annual closing date) to explore the relevance of scientific approaches to tackling sustainability challenges and provide them with an opportunity to present their perspectives. The competition is sponsored by the Royal Society of Chemistry, a leading voice for the chemical sciences and their role in sustainability.[10]

Essays that are very highly rated in the judging process are selected as Finalists, from which the Regional Winners are identified, with regions being defined according to the World Bank's current geographic classification.[10] Regional Winners each receive a prize of US$ 500 and a Winner's Certificate, and their essays are published in the journal *RSC Sustainability.* Entrants whose essays are selected as Finalists also receive a Winner's Certificate, and their essays are published in an annual IOCD Compendium online.

The results of the annual competitions in 2023-2024 can be found on IOCD's website.[11]

Results of the 2025 competition

The theme of the 2025 IOCD Essay Competition was *From waste to wealth: how chemical sciences can sustainably transform waste into valuable products*.[12,13] From over 180 entries, evaluation by volunteers from around the world recruited by IOCD provided a short-list of 67 essays for further assessment, which led to 43 being selected as Finalists. These were then grouped by region[14] for judging the Regional Winners. The seven essays designated as 2025 Regional Winners were published[14] online in October 2025 and included in 2025 issue 11 of *RSC Sustainability* as detailed below.

Essays from the 36 additional Finalists in the 2025 competition are published in this compendium, available on IOCD's website (https://www.iocd.org). They provide further stimulating examples of the perspectives of young people on chemistry's role in the transformation of waste to wealth. This year's cohort of entrants spanned the age range 11-34 years (about 20% were aged under 18 at the competition's closing date and two were in the 2025 Finalists group from which the Regional Winners were chosen). The essays from Finalists covered a very wide range of topics related to minimizing and valorising waste from many different sources, including agro-industrial biowaste from plants and animal products such as bone, dung and hide, electronic and electrical equipment, fungi, nuclear reactors, plastics, renewable energy conversion and energy storage, and wastewater. There was attention to minimising waste production and optimising recycling – e.g., through application of a range of techniques and tools including, mechanochemistry, optimization of reaction parameters, quantum chemistry and systems thinking, as well as highlighting waste conversion to particular types of high-value products or feedstocks such as aviation fuel, biochar, biopolymers, carbon nanodots, CO_2 for synthesis, lignin and phosphorus compounds. Many of the essays drew attention both to the need for more research and to the importance of engagement with policy-makers, industrialists and other sectors of society to ensure that better technologies are developed and widely adopted.

We are extremely grateful to the Royal Society of Chemistry for sponsoring this competition, through providing financial support to help cover the costs of operations and by participating in the competition process and publication of the Regional Winner essays. We are also extremely appreciative of the work of the dozens of volunteer evaluators from around the world, who assist us in reviewing the entries and selecting the Finalists and Winners. Most of all, we greatly appreciate the efforts made by young people around the world to write fascinating essays and to submit them for our scrutiny.

IOCD will continue to operate this annual Essay Competition, *Young Voices in the Chemical Sciences for Sustainability*, offering each year a new topic on which young people can express their perspectives. Members of the chemistry community of all ages are invited to join us – whether as entrants, evaluators or promoters of the competition. Further information can be found on IOCD's website (https://www.iocd.org), or by writing to essay@iocd.org.

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Regional Winners

Regional Winner
East Asia and Pacific

The new gold rush: unlocking potential of waste through chemical science, society and policy

Yick E. Chew

Research Centre for Sustainable Technologies, Faculty of Engineering, Computing and Science, Swinburne University of Technology, Sarawak, Malaysia

Yick CHEW in Malaysia begins by identifying examples of varieties of waste occurring in solid, liquid and gas forms and the different extents to which they are recycled through chemical and biochemical processes to transform them into valuable products. Developing his essay in three parts, he first considers the merits of using catalysis, which may simultaneously speed up chemical reactions, lower power consumption and decrease operating costs. The use of dual-functional materials for the methanation of CO_2 captured from flue gas and other examples are described in the text. The second part highlights the value of mathematics and computer simulation. Kinetic modelling can determine the optimum conditions for a chemical reaction to take place. At the same time, computational tools are useful to identify the most cost-effective pathway for a given transformation. The third section of the essay outlines the important role played by consumers and industries in the development and generalization of waste-to-wealth practices. Moreover, important practices including life-cycle assessment, circular economy, and accurate sorting of end-of-life products for recycling are highlighted, which are conditioned by education as well as by suitable national regulations and policies – and require commitment and action by everyone.
Article at: *RSC Sustainability*, 2025, https://doi.org/10.1039/D5SU90047F

Regional Winner
Europe and Central Asia

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

Frederica Butler

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Frederica Butler in the UK considers the role of the circular economy to help keep products and materials in use for as long as possible in closed-loop systems. The chemical sciences contribute 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. She discusses three areas of application, the first being carbon capture and utilisation to produce materials such as methanol, formic acid and recyclable plastics She emphasises that processes employing CO_2 as a starting material need to be designed and assessed to ensure that the potential environmental benefits from the recovery and reuse of CO_2 outweigh the negative effects of energy and materials required for the transformations involved. Her second example focuses on the recycling of plastics, including emerging methods for depolymerisation such as heterogeneous catalysts and photocatalysis. She emphasises both the regulatory roles that governments can play and the need for technological improvements in polymer design, to strengthen the contribution of recycling in dealing with plastic waste. Finally, she addresses the challenge of waste electronic and electric equipment (WEEE) and the value or recovery of components such as precious metals.
Article at: *RSC Sustainability*, 2025, https://doi.org/10.1039/D5SU90053K

Regional Winner
Latin America and the Caribbean

Waste alchemy in the age of Industry 5.0: rethinking sustainable electronics

João V. Paulin

São Paulo State University (UNESP), School of Sciences, Department of Physics and Meteorology, Bauru, Brazil

João Paulin in Brazil focuses on sustainable electronics in the context of Industry 5.0 – the latest era of industrial innovation, which combines automation and artificial intelligence with sustainability and human-centred approaches while emphasising environmental responsibility and circular economy principles. He takes as his starting point the large amount of agricultural and food industry waste being generated and the opportunity to use advances in green chemistry and materials science to transform the natural organic materials (NOMs) contained in this waste into functional electronic components. His essay recognises the challenges faced in achieving this, beginning with the difficulties presented for standardization and reproducibility due to the natural variability seen in NOMS. He then exemplifies ways that the chemical sciences can overcome these, providing efficient methods for extraction, modification, and functionalization of NOMs using green approaches such as deep eutectic solvents, supercritical fluids, and enzymatic processes, as well as ultrasound and microwave-assisted extraction. These can help in creating materials such as biopolymer-based conductors, bio-inspired nanocomposites, and naturally derived semiconductors, for example via biochar, with the resulting products potentially being biocompatible, biodegradable and functionally versatile. The essay also discusses ethical, social, and economic considerations and the importance of fostering eco-conscious consumer behavior.
Article at: *RSC Sustainability*, 2025, https://doi.org/10.1039/D5SU90048D

Regional Winner
Middle East and North Africa

To scale or not to scale? Re-engineering biorefining for a more sustainable and circular future

Ahmad B. Ghanayem

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Ahmad Ghanayem, who is from Jordan and presently researching for a PhD in the UK, focuses his essay on biorefining techniques. He begins by countering the common misconception that a process is sustainable merely because it uses waste as feedstock. As an example, he discusses the bio-sourced synthesis of lactic acid where, as often encountered in industrial syntheses, product recovery involves an energy-intensive downstream separation of materials by distillation. Reactive distillation, instead of conventional distillation, may save a lot of power cost. Indeed, along the entire pathway leading to the final product, close scrutiny is required before a transformation process can be declared sustainable and scaled at the industrial level. Many parameters must be examined, with energy consumption and CO_2 emission being important but not the only factors. In some cases, replacing chemical catalysts by biocatalysts can be very useful, since the latter usually require milder conditions as well as being renewable and sometimes cheaper. Ghanayem takes the production of styrene by an enzyme-catalysed reaction as an example. He concludes that much remains to be done before more biorefinery reactors can take over from conventional all-chemical transformation plants and this reform will require close collaboration between biologists, chemists and industrialists.
Article at: *RSC Sustainability*, 2025, (https://doi.org/10.1039/D5SU90051D

Regional Winner
North America

Shining light on waste: photochemical strategies to reduce and transform plastic pollution

Alexandra Barth

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Alexandra Barth in the USA, focuses on the urgent need to tackle major environmental problems caused by the widely-produced, non-biodegradable polymers that contain a strong backbone, such as polyethylene (PE) polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC). She highlights the potential of photochemical reactions, which work in mild conditions and offer improved energy efficiency and reduced greenhouse gas emissions, with photocatalysis being used to upcycle resistant polymers via breakdown into small oxidized molecular fragments to provide feedstocks. The breakdown mechanisms she describes involve the formation of backbone carbon radicals resulting from breaking C—H bonds, which then oxidise to alkylperoxy radicals that undergo repeated *ß*-scission. In this way, for example, PS can be oxidatively fragmented to benzoic acid, at least on a laboratory scale. Detailed knowledge is less advanced regarding the photocatalytic oxidation of PE, PP and PVC, but all three polymers also yield formic acid and, in the case of PP, acetic acid as well. In the last part of her essay, Barth explains different strategies that might allow the scale of plastic waste upcycling to be increased from grams to tons, with flow photoreactors constituting a promising approach and the use of solar light further increasing the sustainability of the photochemical reactions.
Article at: *RSC Sustainability*, 2025, https://doi.org/10.1039/D5SU90049B

Regional Winner
South Asia

Reimagining plastic waste: sustainable depolymerization using mechanochemistry as a gateway to high-value applications

Emal Mathew

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Emal Mathew from India, currently pursuing Master's studies in Germany, devotes his essay to the recycling of plastics. After noting the two main ways (mechanical and chemical) currently used to recycle plastics, he focuses on mechanochemistry. This is a long-known technique, based on employing mechanical forces to initiate or facilitate chemical reactions, that is now regaining attention and being recognised for its value in the transformation of plastics. For example, the impact and shear forces generated in ball milling can lead to breaking the C—C bond backbone of a polymer such as polymethyl methacrylate, polystyrene (PS), and polypropylene, leading to homolytic cleavage. The derived radical intermediates undergo recombination, disproportionation, H-abstraction, and addition reactions, with eventual formation of small-molecule products. Mathew notes that the solvent-free reaction conditions, operating at ambient conditions, can lead to 80% fragmentation of PS to the monomer. Complete mechanochemical depolymerization of polyethylene terephthalate through solid-state ball milling with NaOH and degradation of polyolefins are other important examples cited. Nevertheless, the scalability of mechanochemistry for recycling plastics at an industrial scale presents challenges that require intensive further work. The essay closes with examples of many high-value applications that the monomers obtained by plastic waste transformation may have.
Article at: *RSC Sustainability*, 2025, https://doi.org/10.1039/D5SU90052B

Regional Winner
Sub-Saharan Africa

From waste to wealth: advancing e-waste transformation through chemical sciences

Emmanuel A. Oke

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Emmanuel Oke from Nigeria and currently a postdoctoral research fellow in South Africa, explores the sustainable recovery of valuable metals from e-waste. Printed circuit boards (PCBs) contain a complex mixture of valuable metals, such as Au, Ag, Cu, and Pd, alongside hazardous substances like Pb, Hg, and brominated flame retardants, as well as non-metals like Si and small amounts of ceramics and glass fibres. After efficient sorting and disassembly (which can now be facilitated by computer-based recognition and robotic automation), the recovery of metals and other products can be made more sustainable through green chemistry approaches. Oke exemplifies the applications of ionic liquids, deep eutectic solvents and organic acids such as citric acid, for the selective and high-yield recovery of diverse metals from e-waste. He also emphasises that the circular economy concept requires that products be designed for reuse, recycling, and resource recovery, as well as pointing to the importance of attention to process factors in the recovery stage, including the development of solvent regeneration techniques. Furthermore, he stresses the importance of supportive policies alongside active societal participation, with governments and international bodies taking a leading role in encouraging responsible e-waste management, as well as collaboration between researchers, industry stakeholders, and policymakers.
Article at: *RSC Sustainability*, 2025, https://doi.org/10.1039/D5SU90050F

Finalist

Not all waste is wasted: how chemical sciences transform waste into wealth

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Nowadays, waste management is one of the most pressing global challenges, exacerbated by industrialization and consumerism. Each year, more than two billion metric tons of municipal solid waste (MSW) are generated worldwide, and this amount is expected to rise by approximately 70% by 2050, placing even greater strain on the environment.[1] Chemical sciences offer innovative solutions to this crisis by transforming waste into valuable resources. In this essay, I explore how chemical sciences drive innovations in waste-to-energy technologies, biodegradable plastics, enzymatic recycling, and circular economy models—key strategies for transforming waste into a resource while ensuring environmental sustainability, economic feasibility, and effective policy implementation.

Figure 1: Innovative chemical science approaches to waste management

Waste-to-energy technologies

In response to the increasing waste generation and energy needs, waste-to-energy (WTE) technologies prove to be an innovative approach to sustainability by converting waste products into energy such as electricity, heat, or fuel. WTE utilizes incineration, gasification, and pyrolysis as ways to reduce landfill waste and at the same time, it produces energy for a sustainable future.

A notable example of WTE's success is Sweden, where 34 WTE plants provide electricity to 780,000 households and heating to 1.45 million homes, significantly reducing landfill dependence while generating cleaner energy.[2] This initiative is a very important factor in the achievement of the set of Sustainable Development Goals (SDGs), namely SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities), and SDG 12 (Responsible Consumption and Production) through waste-to-energy conversion. Sweden's WTE success highlights the potential of waste as an untapped energy source, transforming environmental challenges into economic opportunities. This approach not only reduces waste accumulation but also supports energy diversification and sustainability efforts.

However, the issue of the carbon emissions resulting from incineration is still a concern, which, if not properly regulated, can contribute to the problem of air pollution. Gasification presents a viable alternative by heating waste in a low-oxygen environment, producing syngas, a versatile fuel with applications in electricity generation and synthetic chemical production.[3] By reducing pollution from combustion, gasification offers a cleaner energy solution aligned with SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) by minimizing air pollution.

Pyrolysis is another method that has emerged as an excellent alternative for the management of plastic waste. In South Korea, the Korea Institute of Energy Research (KIER) and the Korea Research Institute of Bioscience and Biotechnology (KRIBB) successfully developed a highly efficient pyrolysis process that converts waste plastics into high-value raw materials while significantly reducing greenhouse gas emissions. By combining chemical and biological processes, they refined pyrolysis oil into normal paraffin, which microbes transformed into dicarboxylic acid, a key component of sustainable plastic production.[4] Such development goes in line with SDG 12 (Sustainable Consumption and Production) which aims at reducing the input of materials from natural resources in the production of plastic goods and the waste of these materials.

As the world is under an increasing burden of waste and the need for sustainable energy, an effective international system to support waste-to-energy (WTE) technologies that would meet stringent environmental and safety standards is of utmost importance. The Stockholm Convention on Persistent Organic Pollutants (POPs) is a legally binding treaty aimed at protecting human health and the environment. It is supported by the Basel and Rotterdam Conventions, creating a comprehensive framework for managing hazardous chemicals and wastes throughout their life cycle. This “cradle-to-grave” approach ensures that most POPs, many pesticides, and all chemicals as waste are regulated under the Basel Convention.[5] For global sustainability to be truly advanced, WTE policies must become an integral part of these conventions making sure that energy recovery is not at the expense of environmental and human health.

Biodegradable plastics

A sustainable future demands transformative solutions to the growing crisis of plastic waste, and biodegradable plastics present a promising alternative to conventional petroleum-based materials that persist in the environment for centuries. Designed to decompose naturally, these materials can significantly reduce waste accumulation and support a circular economy. However, their success depends on well-developed waste management systems, industrial composting infrastructure, and strict regulatory frameworks to prevent them from becoming another source of pollution. Without these, biodegradable plastics may contribute to pollution instead of providing a sustainable alternative.

In the Philippines, groundbreaking research at the University of the Philippines Los Baños has resulted in the development of polyhydroxyalkanoates (PHAs), a type of biodegradable plastic derived from bacteria, which under natural conditions will break down within a month.[6] PHAs differ from conventional plastics as they are produced from renewable resources and decompose without leaving harmful microplastics behind. This development aligns with SDG 9 (Industry, Innovation, and Infrastructure) by promoting scientific breakthroughs and SDG 12 (Responsible Consumption and Production) by encouraging the implementation of environmentally-friendly methods of packaging and production.

Similarly, Indonesia’s Avani has pioneered cassava-based biodegradable bags that dissolve in warm water and pose no threat to wildlife if ingested.[7] By utilizing renewable agricultural resources, these bags not only reduce plastic waste but also generate economic opportunities for local farmers and industries. This aligns with SDG 8 (Decent Work and Economic Growth) by supporting green jobs and SDG 14 (Life Below Water) by preventing plastic accumulation in marine ecosystems.

Despite their potential, biodegradable plastics can only succeed with strong infrastructure, strict regulations, and public awareness. Without industrial composting, they often end up in landfills or oceans, worsening pollution. Governments must invest in composting facilities, enforce Extended Producer Responsibility (EPR) policies, and standardize labeling to prevent confusion. A well-regulated circular economy is key to turning biodegradable plastics into a sustainable solution rather than a short-term fix.

Enzymatic recycling

In the fight against plastic waste, conventional recycling often falls short, as the quality of plastic declines with each cycle. Enzymatic recycling addresses this issue by using engineered enzymes to break plastics down into their original components, allowing for high-quality reuse without degradation.[8]

A leader in this innovation is Carbios, a French biotechnology company that has developed enzymatic recycling methods for PET plastics and textiles. This process reduces greenhouse gas emissions by around 30% compared to virgin plastic production.[9] Furthermore, Carbios has successfully produced the world's first t-shirt made entirely from 100% recycled textile waste, a critical breakthrough given that only 1% of textile fibres are currently recycled into new fibres.[10]

Despite its vast potential, enzymatic recycling must be seamlessly integrated into a circular economy, ensuring alignment between waste management, production, and policy. This approach requires designing plastics for enzymatic breakdown, scaling biorecycling infrastructure, and embedding enzyme-based solutions into manufacturing. By prioritizing innovation-driven regulations and industry collaboration, enzymatic recycling can transition from an emerging technology to a mainstream pillar of sustainable waste management.

The circular economy approach

The innovations discussed in this essay, including waste-to-energy technologies, biodegradable plastics, and enzymatic recycling, play a crucial role in advancing a circular economy, a system designed to eliminate waste, keep materials in continuous use, and maximize resource efficiency. The circular economy, as a dual-loop regenerative system, emphasizes sustainable resource use to enhance both environmental and economic performance.[11] One example is waste-to-energy technologies, which generate heat and electricity, remove hazardous substances, recover metals and phosphorus, and reduce greenhouse gas emissions, contributing to a circular economy.[12] Similarly, biodegradable plastics enhance circularity by using sustainable alternatives to petroleum-based materials, consuming less energy, and reducing carbon dioxide emissions by up to 70% compared to conventional plastics.[13] Enhancing this process, enzymatic recycling uses biological catalysts to depolymerize polyethylene terephthalate (PET) into its original building blocks, enabling high-quality reuse while reducing reliance on virgin materials and minimizing environmental impact.[14] By integrating these innovations into production and waste management systems, the circular economy shifts waste from an environmental burden to a valuable resource, creating a more sustainable and efficient global economy.

However, while technological innovations are crucial for promoting a circular economy, they must be complemented by systemic reforms, effective policies, and changes in consumption and production patterns. Governments need to enforce Extended Producer Responsibility (EPR) policies, businesses must adopt sustainable supply chains, and consumers should actively contribute to waste reduction. Achieving a circular economy is a shared responsibility that relies on collaboration between science, industry, and society.

Conclusion

The approach to waste management adopted today will have a profound impact on the well-being of future generations. Chemical sciences offer innovative solutions to turn waste into valuable resources, but progress depends on strong policies, corporate accountability, and public participation. Without these, even groundbreaking advancements may fall short. Societies must choose: continue unsustainable waste accumulation or embrace a future where waste drives innovation and sustainability. Science has provided solutions—now, collective action must follow.

Statement on use of AI

No AI technology was used to prepare the essay.

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Finalist

Philosopher's stone: from biomass waste to functional carbon nanodots

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Transforming wastes to wealth is the new normal for sustainable growth; especially when we consider how human actions in the past and the present have led to series of negative impacts on our environment. Impacts in the form of global warming, diseases, floods, as well as polluted waters that significantly endanger terrestrial and aquatic inhabitants are all attributed to multiple careless human actions. An instance in such actions is seen in environmental pollution caused due to piling up of wastes. In developing countries like Nigeria, piled up wastes are moved from one place to another and subsequently end up in water bodies; or even worse, burnt. But the reality is the waste still remain either directly with us or in the water bodies that we utilize as the source for fish and drinking water or in the air we breathe. Unless we transform that waste into something we can use, the negative impacts from it will only increase. However, the expenses at which the waste is transformed sometimes could be unsustainable. In recent years, researchers are interested in functional nanomaterials due to their ease of preparation, diverse applications and various starting materials. Interestingly, carbon nanodots (CDs) are a new form of carbon nanomaterials that have diverse applications in medicine, photocatalysis, sensing and electronics.[1–3] Furthermore, these CDs could be made from various starting materials (**Figure 1)**. The most interesting part is that, the CDs could be made from various kinds of organic wastes and/or plastic wastes. This means that we can transform the troubling waste into useful and valuable functional CDs. Metaphorically, waste is a Philosopher's Stone as it is transmuted into "golden" nanomaterials (CDs). In this essay we try to address the following questions:

1. What is carbon nanodot?
2. How are they made?
3. Is it "worth it" to invest into the sustainable development of carbon nanodots?
4. What is the current stage in carbon nanodots related researches?
5. What value could these materials add to our daily life?

Firstly, carbon nanodots or CDs are small sized nanoparticles. In other words, they are small particles with sizes in the nanoscale range, typically below 10 nm. They were first discovered unexpectedly by Xu *et al*[4] in 2004. Since then, developments in terms of its synthesis method, applications and characterizations have been reported.[3,5] CDs possess characteristic properties similar to quantum dots (QDs) such as the ability to absorb light in the ultraviolet (UV) region and emit visible blue, green, yellow or red light (fluorescence). In comparison to CDs, QDs requires toxic metals such as indium and cadmium. This is concerning because current QDs production for Quantum dot Light-Emitting Diode (QLED) consumes up to 150 tons of indium and 50 tons of phosphorus annually.[3] Additionally, CDs possess robust surface functional groups that are tunable for numerous applications. Therefore, CDs having diverse potential in various fields are regarded as more sustainable alternatives to QDs.

In addition, their synthesis could be broadly classified into two approaches. The first approach involves crushing a bulky material (such as graphene) into a small nanodot rich in carbon. The approach is called top-down because it starts with a bulky precursor and ends with ultrasmall CDs as the products. The second approach is directly opposite to the first approach. It is termed "bottom-up approach" and it involves the chemical conversion of small organic molecules-pure molecules or molecules contained in organic matter, into bulkier nano-scaled carbon nanodots. For greener and more sustainable synthesis approach, the bottom-up approach is usually adopted. There are different types of methods under this category. The methods include pyrolysis, hydrothermal/solvothermal and microwave.[2,3] It is pertinent to consider the starting material for the development of CDs. This is because avoiding petroleum-based precursors could save up to 4,500 tons of petroleum and prevent the emission of 14,000 tons CO_2 in the atmosphere.[3] Furthermore, the precursors could influence the overall property of the resulting CDs especially for applications where the CDs interact with biological system.[2] Therefore, deciding on what type of precursor to use could aid tuning the properties of the resulting CDs. In **Figure 1**, Hamed *et al*[6] listed various precursors used to synthesize CDs. In summary, sustainable and green synthesis of CDs is done via the bottom-up approach. Biomass starting materials are employed in order to reduce the use of petroleum-based materials as well as tailoring the overall property of final CDs.

Figure 1. Various green and sustainable precursors used for the synthesis of carbon nanodots (CDs). Reproduced with permission from[6] Copyright (2024)

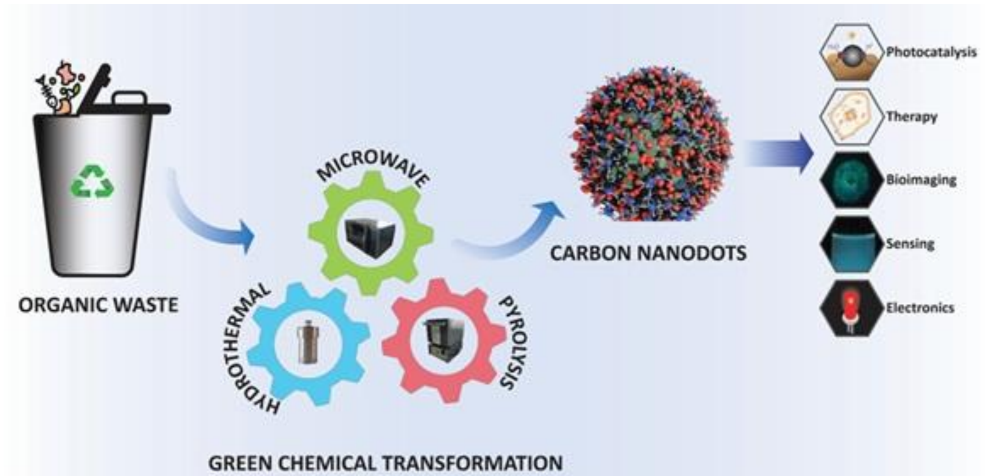
Moreover, it is very important to emphasize what it means to synthesize carbon nanodots sustainably. First and foremost, the term sustainability in this situation implies that we effectively design, nontoxic carbon nanodots with the aim of protecting and enhancing human health and the environment.[7] When sustainable chemical approach is applied in CDs development, the following benefits described by Zuin *et al* [7] could be achieved. They are:

- Avoiding the use of toxic and hazardous materials.
- Use of renewable starting materials instead of non-renewable ones.
- Reducing undesirable environmental impacts during and after the synthesis.
- Providing economically competitive and advantageous technologies for industry.

Each of the above-mentioned benefits could be directly translated to one or more stages of CDs production. Generally, complete CDs' synthesis process follows four stages,[3] that is, pre-treatment, chemical conversion, purification and processing. Taking pre-treatment stage as an example, as described by Ren *et al*[3] simple drying in an oven at 100^{o}C consumes 35 kWh electricity in 4 hours for 1kg CDs production. If this electricity is generated from a petroleum a powerplant that consumes petroleum, about 8.4kg of petroleum would be required to produce 1kg of CDs. However, similar drying could be achieved by using renewable solar irradiation. Next stage for chemical conversion of precursor to CDs could be achieved by dry pyrolysis or microwave-assisted heating thereby reducing the use of toxic solvents. Furthermore, the hydrothermal method uses water which is renewable and nontoxic as a solvent. In fact, the use of biomass waste as starting material reduces potential environmental pollution. Similar could be realized for the remaining production stages; thus, sustainability could be regarded as one of the advantages that CDs have over their counterparts (QDs).

Keeping that in mind, now we can explore the potential applications of CDs synthesized by sustainable and green approach in the past decade. Numerous researchers have developed CDs from sustainable sources for detecting metal ions. Few review articles are already available that summarize these CDs and their applications.[6,8] An example of these studies was reported by Ramanan and co-researchers.[9] In this study, the researchers were able to convert non-biodegradable expanded polystyrene (EPS) waste into multi-functionalized CDs for selective and sensitive detection gold ions (Au^{3+}) in water as fluorescent probes. Similarly, applications of sustainable CDs for bioimaging have been reported in numerous studies.[8] Bioimaging application of these biocompatible CDs could be used to detect cancer cells thus useful in diagnosis *in vitro* and *in vivo.*[10] Apart from diagnosis, these CDs could also be used as potential therapeutics for treating various diseases such as cancer [2,5,10] and drug delivery,[10,11] among others. Some CDs exhibit dual functions as diagnostic and therapeutic agents (theranostics).[10,12] Furthermore, due to their intriguing optical properties, sustainable CDs could be used in photocatalysis for light induced degradation of dyes or toxic organic compounds. For example, methyl viologen, a toxic organic compound, was shown to be degraded by CDs acting as photocatalysts.[13] More discussion on their sustainable photocatalytic applications were reported.[14] Rosso *et al* [15] reported the potency of CDs as nano-organocatalysts for synthesis applications. This is aimed at reducing the use of metal organocatalysts for synthesis applications. Even the waste from CDs synthesis could be used in battery technologies.[3] Other applications of CDs as anti-counterfeiting inks[3,16–18] and in electronics[17,19] were investigated. In summary, CDs shows numerous sustainable applications that could significantly reduce health and environmental concerns while displaying enhanced properties when fully developed.

To conclude our discussion, we have seen that CDs are such sustainable materials that we can develop from waste by employing cost effective green and sustainable synthesis approach and subsequently apply them for numerous applications including assuaging water pollutions (**Scheme 1)**. In other words, we can summarize them as "valuable nanomaterials generated from waste and used to fight health and environmental concerns sustainably". Large scale production of these CDs is achievable and was already reported.[18,20,21] However, realizing the practical benefits of these CDs requires further investigations in terms of their toxicity. Even though current studies reported their low toxicity, more studies are needed to evaluate their toxicities over longer period. Moreover, advanced studies and investments are needed to scale-up their applications from laboratory to industrial level. The main purpose of this essay is to metaphorically introduce waste as a "Philosopher's Stone" in terms of the ability to practically use the waste to produce valuable nanomaterials i.e. carbon nanodots. Hopefully, this awareness could increase interest in CDs' research and developments.



Scheme 1 Schematic summarizing the transformation of wastes to functional carbon nanodots.

Statement on use of AI

No AI was used in the preparation of this essay.

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Finalist

Quantum chemistry in waste-to-wealth technologies

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Introduction

Municipal solid waste generation will increase by 2050, from 2.3 billion tonnes in 2023 to 3.8 billion tonnes, worsening environmental degradation and resource depletion. Recognising the expanding challenge, the United Nations Environment Programme (UNEP) works globally with governments, businesses, and civil society to promote sustainable waste management solutions.[1] However, traditional waste management strategies are still inadequate. What if cutting-edge scientific advances, such as quantum chemistry, could convert this growing trash into valuable resources?

Earth has been surviving as a fossil-based economy with major sources of energy, including coal, petroleum, and natural gas, leading to a gradual decline in the available resources. The transition from a fossil-based economy to a completely renewable one has been a substantial and slow challenge, with larger implications for addressing wastes generated to craft a beneficial resource. Wastes produced are further processed to fabricate innumerable materials such as biopolymers.[2,3] Henceforth, the invention of the waste-to-wealth concept focuses on transforming waste materials into valuable products that can address the combined challenges of waste management and scarcity of resources. This paradigm shift is predominantly relevant to the field of chemistry, where novel approaches are being developed to transform waste into usable materials. The waste-to-wealth strategy aims to reduce environmental pollution and the burden of waste and convert it into a resource, such as carbon sequestration from byproducts and reuse in the steel industry.[2-5] Various approaches have been developed for the sustainable development of usable products from waste. Quantum chemistry has emerged as an extremely powerful tool to advance waste-to-wealth processes that overcome the challenges faced by traditional waste management techniques, such as effectiveness and environmental sustainability. This applies quantum mechanics to chemical systems, provides unparalleled catalyst and reaction route design accuracy, resulting in more effective waste conversion procedures. A comprehensive understanding of the electronic structure of molecules and mechanisms of the chemical reactions thus enables increased efficiency in the design of catalysts and optimisation of the reactions and their pathways. This essay explores the transformational effectiveness of quantum chemistry in waste-to-wealth applications and addresses the catalyst design and chemical reaction optimisation, and the revolution of the waste conversion processes, making them more effective, energy-efficient, and ecologically benign, as well as the limitations of such approaches and their future opportunities for innovation.

Quantum chemistry in waste conversion

Quantum Chemistry is based on the principle of the Schrodinger equation that enables the determination of the electronic structure of molecules, the distribution of electrons and the energy levels of molecular orbitals, which aid in understanding the reactivity of various chemicals and design catalysts to facilitate specific reactions. It employs computational methods to model chemical reactions, predict the properties of molecules, and develop novel materials and catalysts. It plays an important role in the development of efficient catalytic methodologies for the conversion of wastes. A few prominent examples include the degradation of plastics, recycling of electronic wastes, use of biowastes for the synthesis of biopolymers and use in green synthesis.[3,6,7] Quantum chemistry enables the sustainable development of catalysts that are capable of breaking down non-biodegradable plastics into their constituent monomers that can further be utilised to synthesise high-quality plastics. The recycling of polyethene terephthalate (PET) wastes, a commonly used plastic in the packaging industry, into valuable materials has been studied extensively. Jiang et al have detailed the recent development in sustainable PET waste upcycling, with the advantages of using thermocatalytic methods. Molybdenum dioxide-carbon (MoO_2/C) catalysts were used for solventless PET depolymerisation, resulting in 87% yields, and PET's high carbon content (~60 wt%) allows for thermocatalytic conversion into important carbon compounds, thereby promoting further study on renewable energy-driven waste management.[8] With a thorough understanding of the electronic structure of the catalysts and reaction intermediates, one can design selective catalysts to cleave the bonds in PET for increased efficiency in depolymerisation.[9]

Similarly, Fatema et al. investigated the recycling of electronic garbage, or e-waste, to recover valuable metals and achieved an effective recovery rate of 72.69% over five days with a 50:50 mixture of ferrous and ferric sulphate.[10] Various valuable metals such as gold, silver and certain rare earth elements have been used in the production of electronics and electric vehicles. However, their recovery is challenging because of the complex composition of the waste materials and the need for the separation processes to be selective to the element of interest. Alongside, Petrus et al. have looked into biomass conversion to biofuels and offer a sustainable and renewable alternative to fossil fuels.[11] However, the complexity of the biowaste materials and the need for selectivity and efficiency in the catalysis hinder the conversion. Hydrolysis of cellulosic biomass has been studied to facilitate the production of biofuels with high yields and cost-effectiveness.[12,13] Quantum chemistry with computational calculations can aid in the design of catalysts as well as ligands that can bind selectively and extract the elements from e-waste by predicting binding affinity to the elements, break down biomass into fermentable sugars, which can then be used to generate biofuels and address the challenges of cellulose.[14] The use of computational methods, such as Density functional theory (DFT) and ab initio calculations, allows researchers to simulate chemical reactions and identify the most favourable reaction pathways.[15,16] These methods provide detailed insights into the electronic structure of reactants, intermediates, and transition states, enabling the design of catalysts that can facilitate specific reactions with high selectivity and efficiency. Certain catalysts designed based on this are quantum dots (QDs), semiconductor nanoparticles with distinct optical and electrical properties, which render them advantageous in various applications such as fluorescence imaging and biomolecule identification because of their size-dependent emission and photostability.[17,18] Their fabrication takes two approaches: top-down, which converts bulk materials into nanoscale structures using lithography and etching, and bottom-up, which assembles QDs atom by atom via chemical reactions such as colloidal synthesis. Advanced quantum chemistry techniques, along with functional surfaces, can improve QD synthesis efficiency and sustainability in line with waste-to-wealth plans.[19,20] The flow of waste materials to valuable products using quantum chemistry processes are depicted in Figure 1.

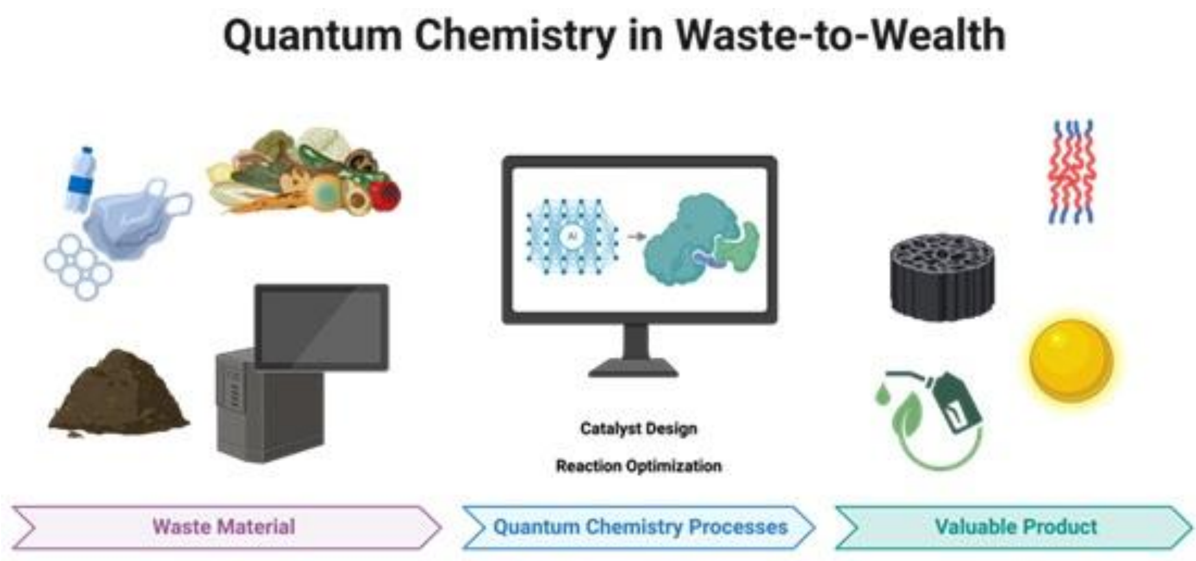

Figure 1 Schematic depicting the role of quantum chemistry in conversion of waste to wealth
Created with Biorender.com

Quantum chemistry enhances waste-to-wealth processes by improving tailored catalyst designs, leading to reduced energy consumption and increased sustainability. Recovering valuable materials from waste benefits both the economy and the environment by lowering the abuse of natural resources, lowering production costs, developing novel revenue systems, mitigating environmental pollution and promoting a circular economy.

Challenges and future scope

Agenda 2030 necessitates region-specific, time-bound initiatives incorporating science, technology, and policy advances. Sustainable chemistry and engineering are critical in addressing such global concerns. Quantum chemistry directly supports the circular economy model by enhancing waste conversion efficiency, minimising dependency on virgin resources, and contributing to Sustainable Development Goals (SDGs) 12 (responsible consumption and production) and 13 (climate action). [21,22] This has been demonstrated in Figure 2. However, a major challenge of quantum chemistry is the high costs, even high resource requirements and scalability of the computational simulations and their implications. Significant resources such as high-performance computing systems and specialised software can often limit access for researchers. The valuable insights are challenging to translate into industrial scale due to the involvement of complex parameters, such as high pressures and temperatures, that might not be aptly captured in the quantum chemical computations. Certain complex wastes also require even more sophisticated designs for catalyst performance and selectivity. Such challenges also need to be addressed with further research.

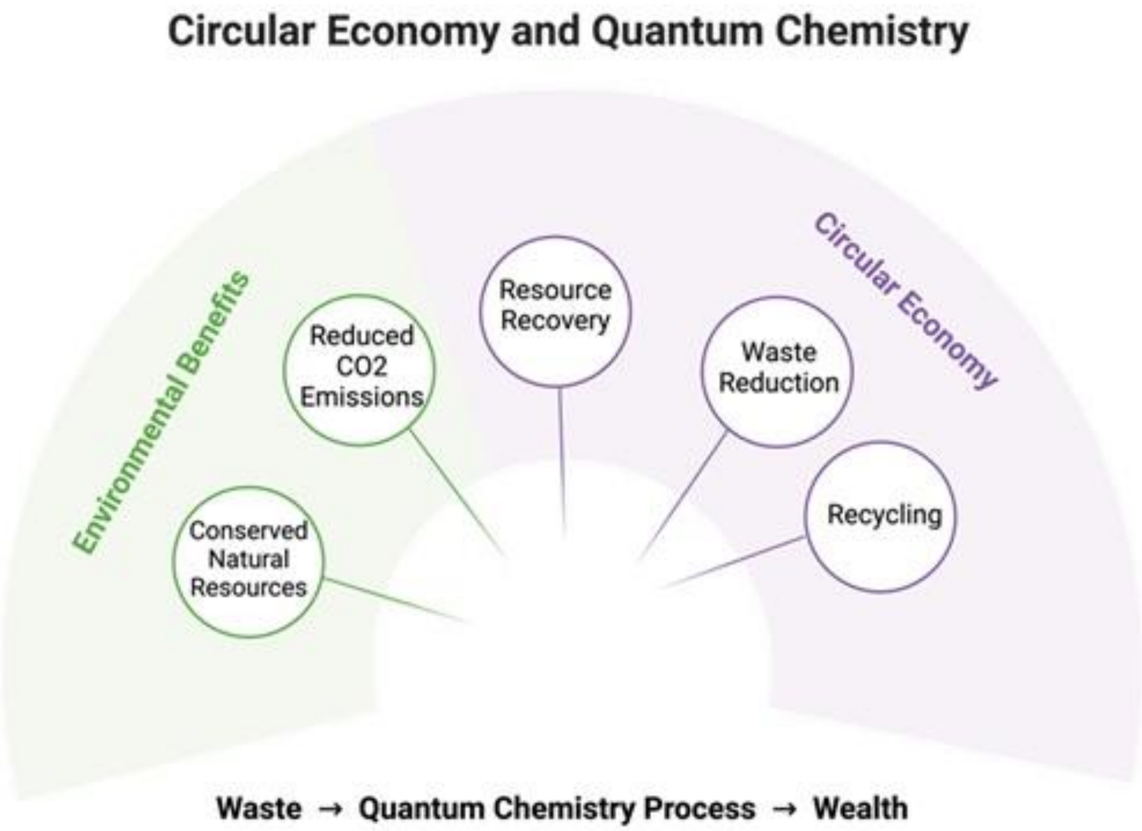

Figure 2 Schematic depicting the alignment of quantum chemistry with the circular economy and minimizing environmental impact
Created with Biorender.com

Traditional computational chemistry encounters substantial problems due to the high cost of solving Schrödinger equations. With the increased employment of artificial intelligence (AI) and machine learning (ML), the computations can be trained with larger datasets and enable faster, more accurate predictions and performance with cloud-based platforms. [23] AI-enhanced quantum mechanical (QM) methods, such as artificial intelligence–quantum mechanical method 1 (AIQM1), combine the precision of high-level QM calculations with the speed of semiempirical approaches, allowing for more precise predictions of molecule structures, reaction kinetics, and spectra. [24-26] This could address the challenging computational costs and time required and increase the accessibility of quantum chemistry to interdisciplinary research. The increase in collaborative efforts can thus facilitate the development of novel methodologies for computation, design and optimisation of waste conversion processes.

Conclusions

Quantum chemistry has greater potential to revolutionise the processes of waste-to-wealth. By delivering a comprehensive understanding of the electronic structure of molecules and the underlying mechanisms of chemical reactions and addressing the constraints, quantum chemistry can augment efficiency, decrease the consumption of energy, and advance the efficacy of novel, untapped, sustainable solutions for waste management and contribute to the transition to a circular economy. Investing in quantum-driven solutions allows us to transform today's trash into tomorrow's wealth, changing industries and saving the earth for future generations.

Statement on use of AI

AI was used in the preparation of this essay to paraphrase some text in order to improve word choice and clarity in English.

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Finalist

From mixed waste to high-value bioproducts: chemical advancements for a circular bio-economy for plastics

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Plastics play an indispensable role in modern society due to their outstanding durability, mechanical strength, and lightweight properties, yet their environmental impact is alarming. The current "take-make-use-dispose" linear model of plastic production and use has led to unsustainable end-of-life (EoL) treatments and resulted in the uncontrolled accumulation of plastics in the environment. Alarming figures show that 79% of post-consumer plastics are either landfilled or indiscriminately disposed of in natural environments such as soils and oceans, while 12% are incinerated and only 9% recycled.[1,2] Further analysis examined the lifespan of plastic products across eight industrial sectors, and revealed that packaging materials, largely thermoplastics, have the shortest lifespan.[1] Not surprisingly, packaging materials are typically discarded within the first year after production.[1,3] Taking into account the enormous volume of packaging waste generated annually, together with its brief lifespan and inadequate EoL management, the packaging sector has become a major contributor to the generation of plastic waste globally.[4,5] Among thermoplastics, polyethylene terephthalate (PET) stands out as one of the most important engineering polymers, widely used in packaging due to its excellent mechanical properties, barrier capabilities, and ease of processing.[6] PET is a synthetic polyester, produced by reacting ethylene glycol (EG) with terephthalic acid (TPA), and it constitutes 8.4% of global plastic production, primarily for beverage bottles.[7] Despite being widely used and extensively considered recyclable, PET's environmental impact remains significant due to inadequate waste management technologies and the ever-increasing scale of production.[8,9] For example, in 2018, Europe alone introduced approximately 4.4 million tons of rigid PET into the market, of which 58.2% was collected through various return initiatives.[10]

Nonetheless, traditional plastic recycling methods rely predominantly on mechanical processes that degrade polymer quality over successive recycling cycles.[11] Additionally, single plastic streams are normally permeated with an array of materials, including bioplastics, different types of plastics, and polymeric composites, which generates hard-to-recycle mixed plastic waste. As a consequence, conventional mechanical recycling methods struggle to process effectively these mixed plastic waste streams, leading to downcycling and continued reliance on virgin petroleum-based plastics. Chemical recycling techniques such as solvolysis[12] and pyrolysis[13] offer an alternative by breaking down polymers into their monomers or other reusable chemical feedstocks. However, if a safe and sustainable by design (SSbD) approach is not fully adopted, these processes can require high energy inputs and generate secondary pollutants.[14] More recently, green catalytic approaches have been developed to improve efficiency and selectivity,[15] including enzymatic degradation that operates under milder conditions and selectively targeting specific polymer bonds. Enzymes such as PET hydrolases and cutinases have demonstrated the ability to depolymerise PET into its monomers to enable re-polymerisation into virgin-quality plastic or other valuable chemical intermediates, demonstrating feasible routes for PET circularity. Expanding these approaches to tackle more complex mixed plastic streams remains a key challenge to advance circular strategies. Therefore, novel chemical and biotechnological strategies have been employed to break down and upcycle these materials into high-value products, such as bacterial nanocellulose (BNC).[16] Progress in the chemical sciences, particularly in depolymerisation and enzymatic degradation, is critical for addressing the limitations of current waste management systems and promoting sustainable solutions towards a circular bio-economy for plastics (**Figure 1**).

Mixed plastic waste streams often contain numerous challenging components, including physically and chemically incompatible fossil- and bio-based plastics.[17,18] The lack of established recycling technologies for bioplastics and their integration within mixed waste streams further complicates their EoL management.[19–21] Biotechnological recycling has emerged as a complementary and environmentally friendly solution for addressing plastic waste that remains difficult to recycle through conventional methods. Advances in PET biotechnological recycling have revealed a growing number of bacterial and fungal strains harbouring PET-degrading enzymes, with over 8000 putative ortholog PETases identified.[22] Highly efficient enzymes such as IsPETase from *Ideonella sakaiensis*[23] and leaf-branch compost cutinase[24] have demonstrated the ability to hydrolyse PET. Furthermore, the integration of chemical depolymerisation with biocatalytic processes has been explored to enhance degradation efficiency.[11] PET degradation products obtained through glycolysis were effectively converted to TPA using the Bs2Est esterase from *Bacillus subtilis* and subsequently transformed into catechol by an engineered *Escherichia coli* strain.[25]

Figure 1 Illustrative diagram of proposed circular journey of mixed plastic waste as it is converted into high-value bioproducts through green-chemical and biotechnological recycling processes

Although enzymatic degradation of PET offers a more sustainable alternative due to its mild reaction conditions and low energy consumption,[26] further optimization is required to improve its efficiency. The thermophysical properties of PET significantly influence enzymatic hydrolysis, as higher amorphous fraction and lower crystallinity improve enzyme accessibility to hydrolysable ester bonds.[27] Studies have shown that the mobile amorphous fraction of PET is more susceptible to enzymatic degradation, as opposed to the rigid amorphous fraction that exhibits lower chain mobility.[28] PETases, lipases, cutinases, and carboxylesterases have all been investigated for their ability to hydrolyse PET into oligomers such as bis(2-hydroxyethyl) terephthalate (BHET), mono(2-hydroxyethyl) terephthalate (MHET), and TPA.[29,30] TPA can then be purified and reused for PET manufacturing, closing the loop in a circular bio-economy.[31] Moreover, upcycling PET hydrolysis products into valuable commodity chemicals and biopolymers such as polyhydroxyalkanoates (PHAs) and lycopene has been demonstrated.[32,33] Thermostable cutinases such as leaf-branch compost cutinase (LCC^{ICCG}) are among the most promising candidates for enzymatic PET degradation, as their ability to operate at higher temperatures improves chain mobility and enhances accessibility to ester linkages.[34] Notably, LCC^{ICCG} has also been reported to depolymerize other biodegradable polyesters such as polycaprolactone (PCL), polybutylene succinate (PBS), polyhydroxybutyrate (PHB), and polylactic acid (PLA).[35,36] The enzymatic degradation of these bioplastics is influenced by polymer crystallinity and biodegradation conditions such as pH and temperature.[37] This suggests that an integrated biotechnological route for degrading mixed fossil- and bio-based plastics is not only feasible but could also offer a sustainable alternative to conventional sorting-intensive recycling processes.

A biotechnological process capable of both degrading and upcycling mixed plastic waste would represent a significant milestone in sustainable waste management. Although bio-upcycling has been largely unexplored, it has the potential to transform plastic debris into high-value materials, as recently demonstrated by the valorisation of HDPE, PS, and PET through chemical oxidation and biological funnelling, enabling the engineered *Pseudomonas putida* strain to convert oxygenated intermediates into PHB.[38] However, the scalability and environmental sustainability of this process remain a challenge due to its reliance on ultra-high purity gases, high pressures, and flammable solvents. Enzymatic degradation presents a safer and more sustainable approach for upcycling plastic hydrolysates into biopolymers such as BNC, which is considered a promising substitute for petroleum-based plastics.[39] Given that BNC production is currently limited by high culture medium costs,[40] utilizing post-degradation plastic debris as a cost-effective feedstock could enhance its economic viability.

Beyond scientific advancements, these innovations have significant economic, environmental, and societal implications. Upcycling mixed plastic waste into high-performance materials creates new market opportunities, reduces dependence on virgin fossil-based plastics, and improves resource efficiency.[41] Environmentally, more effective plastic degradation reduces pollution, benefiting biodiversity conservation and mitigating microplastic contamination. Societally, improving waste management technologies can aid communities suffering from plastic pollution, while engagement with policymakers can help drive regulatory decisions toward sustainable waste management solutions. Despite these promising developments, challenges such as enzyme scalability, process optimization, and interdisciplinary collaboration must be addressed for widespread implementation. With the integration of chemical advances in catalytic depolymerisation, enzymatic plastic degradation, and bio-upcycling strategies, the gap between scientific innovation and industrial application can be closed towards the transition to a sustainable, circular bio-economy for plastics.

Statement on use of AI

AI was used in the preparation of this essay only for the purpose of improving the readability and language of the original draft, after which the author reviewed and edited the final content. The author accepts full responsibility for the veracity and correctness of all material in this publication.

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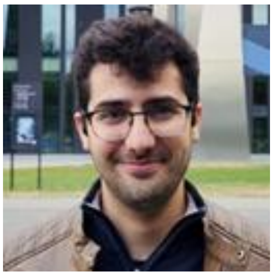
Finalist

Chemical sciences: the bone bio-waste Philosopher's Stone for achieving circular economy



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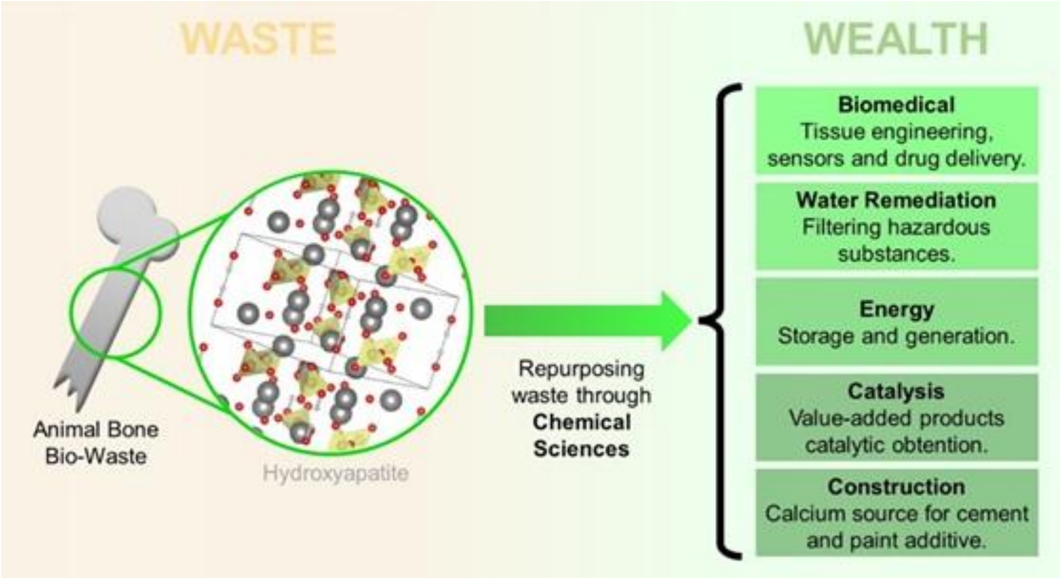
The non-stop consumption model in which our society is based has created the most extreme waste management problem ever seen, supposing a threat to all living life in our planet, including ourselves.[1] Promoting circular economy models has become the main focus of governmental agencies to ensure sustainable societies while protecting the environment and ecosystems.[2-4] In order to achieve it, goals have been set by worldwide agencies involving mainly cutting up on waste generation i.e., expanding goods useful life through reparation, favouring products recyclability or reducing plastic consumption, amongst others.[4] However, when dealing with food/food-waste management, the only topic approached is decreasing the food percentage which is lost due to non-consumption. In the European Union, it is estimated that between 118 – 138 million tonnes of organic waste matter are generated every year being most part of it disposed in landfills or incinerated to produce electric energy, increasing the carbon footprint through greenhouse effect gas emissions in both cases.[5] Since the amounts of residues generated increase every year, it is clear that immediate action needs to be taken to achieve sustainable and efficient bio-waste treatment. Considering that, the game-changing strategy should become finding materials amongst the bio-waste which, through simple and green chemical processes, could be converted into value-added products, thus, avoiding overlooking consumer generated food residues by regarding them as feedstock for advanced applications. To proof how chemical sciences make possible this strategy, the present essay will focus on analysing one specific bio-waste, bones.

Amongst all the bio-waste generated by humans, there is one particular material with lots of potential which has been vastly studied in the literature, animal bone bio-waste (ABB). More than 100 million tons ABB are generated worldwide every year through food consumption,[6] which makes this residue a highly abundant and free feedstock. Essentially, bones consist of ~ 70% hydroxyapatite (HAp) which is a calcium phosphate salt ($Ca_5(PO_4)_3OH$) with high structural stability, having its melting point at 1100 ºC and low solubility (0.3 mg/mL).[7] Despite of being a ceramic, HAp possesses piezoelectric properties and is a natural adsorbent being these particular attributes the main motivation for the scientific community to explore its uses in fields such as: biomedical, water remediation, energy, catalysis and even construction.[8] Nevertheless, repurposing ABB HAp requires employing chemical sciences, as a Philosopher's Stone, to convert or adapt these residues into added-value products capable of fulfilling advanced applications, as seen in Scheme 1.

On the path to convert waste into value, the most direct application for ABB HAp consists of using it in the biomedical field since HAp is a biocompatible material. Loading biogenic HAp to polymeric materials has been reported to enable 3D printing of customized scaffolds offering personalized treatments for bone tissue regeneration.[9,10] Besides, the obtention of this ceramic is not limited to ABB, egg shells have been enhanced through titanium doping and tested achieving boosted bone regeneration and efficient implant incorporation, thus, proving that the HAp source does not affect its osteoconductive properties.[11] As in the former strategy, doping biogenic HAp with metallic oxide expands its capabilities beyond tissue engineering. Iron oxide doped ABB can be used as support platform for efficient detection of biomarkers or controlled drug release.[12,13] Being the key point that these applications could be performed by chemically converting food residues, increasing the biomedical industry competitivity while offering sustainable feedstock for medical products and decreasing the overall carbon footprint.



Scheme 1 Flow chart depicting the importance of chemical sciences to convert waste materials into value-added products, focusing on the specific case of animal bone bio-waste

Switching to the water remediation field, the information age along with all the technologies arising from it has led the world to rely on electronics, resulting in the arrival of new residues such as batteries or computers which contain hazardous metals. Treating and recovering wastewaters extra carefully has become imperative to guarantee environmental health and prevent these substances from reaching our households. Being HAp a natural adsorbent, ABB sources have been studied for wastewater purification, specially, for toxic metals ion removal, such as, Cd^{2+}, Cu^{2+} and Pb^{2+}. Through extremely-simple carbonate addition processes, composites with high adsorption/removal rates can be achieved, thus, offering a promising water-filtering solution.[14-17] Furthermore, through preparation of hollow fibre membranes from cow bones HAp, the former approach has even been extended to textile water contaminants in which dyes, oils and surfactants were removed achieving >80 % performances.[18] It is worth noting that, upon applying simple chemical preparation procedures to ABB HAp, wastewaters generated by industry would be recovered while reusing food residues generated by society, that is, a feasible, abundant and cost-effective solution.

Nonetheless, wastewaters sustainable recovery should start by not employing hazardous metals in first instance. For that, new materials should arise as substitutes for current state of the art electronics which, although same efficiency levels are not likely to be reached, they would offer more sustainable options. As mentioned, HAp is a piezoelectric material and thus, a candidate in the field of energy storage and generation. On one hand, supercapacitors made of ABB HAp (pig bones) have been reported as most competitive supercapacitors amongst biowaste carbon materials upon simple application of thermal and acid treatments.[19] On the other hand, biogenic HAp was used as powder or mixed in polymeric matrices to obtain electricity generating devices which, through human movement, were able to achieve up to 4.1 V under walking.[20,21]

As final examples of ABB based materials, the catalysis field is worth mentioning. Mainly focusing onto biofuels production, several studies reported ABB HAp capabilities for converting cooking oils into biodiesel at mild conditions, offering a green alternative purpose to a household residue.[22,23] Moreover, CO_2 conversion into ethanol has been achieved upon application of a thermal stimulated polarization process to chicken, cow and pig bones HAp which enabled activating them catalytically to employ solar thermal energy, stablishing a green process for this greenhouse effect gas capture.[24] Once more, using food not only enables decreasing residues generated by our society but to also mitigates the carbon footprint which we are producing.

Further applications of ABB could be mentioned in this essay as in construction[25] or using them as phosphate sources for re-fertilizing soil.[26] However, although the applications for this bio-waste material seem never-ending, the number of technologies that make it out of the laboratory into our society is rather surprising: almost zero. Then, how are we supposed to reach the sustainable societies our governmental agencies seek to achieve? Chemical sciences prove to be an immensely powerful tool, enabling converting food residues into materials capable of performing advanced applications sustainably, yet all these achievements remain unexploited. The capitalization of science, where the trends rule what is attention worthy, and the fast publication way to get funding have destroyed the real purpose of science, making the human species go backwards from the real objectives. If we want to keep advancing towards a sustainable future, the following three simple statements should be our priority: 1) No super-complex-expensive materials should be needed to proclaim a breakthrough. Focusing on using sustainable materials and process should be a must rather than achieving the best yield/performance at all costs. 2) Scientists should be responsible for escalating up to pre-pilot the technologies developed. Then, business cases could be prepared giving insights for the potential real-life application or technological transfer rather than publishing and forgetting results. 3) Promoting sustainable chemical sciences to ensure that the generated carbon footprint during products fabrication plus the one after conversion, are compensated through their repurposing. Governmental agencies support is crucial to secure all these premises, which should be closely in touch with the scientific community in order to promote and endorse their fulfilment as well in the private sector.

In conclusion, there is lots of potential in the waste we generate as a society as clearly seen for the specific example of ABB residues. Thanks to the chemical sciences acting as the ultimate tool, we would be able to close the loop achieving sustainable communities benefitting our health and environment. However, taking conscience and working towards feasible implementation and technological transfer should be of uttermost importance to ensure that our efforts reach society and benefit our planet's future.

Statement on use of AI

Use of Artificial Intelligence (AI): No AI was used in the preparation of this essay.

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Finalist

The best waste is no waste: mechanochemistry for the sustainable transformation of waste into valuable products

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The marvels of chemical sciences

Chemical sciences have contributed to the well-being of humankind to an unfathomable extent. Nothing exemplifies this more than the Haber-Bosch process, arguably the most important scientific discovery of the 20th century.[1] Without this invention more than a century ago, which made it possible to synthesize ammonia from its elements on an industrial scale and thus provide fertilizers that enabled a drastic increase in global food production, famine would have been inevitable and today's world population would be billions of people smaller.[1]

It's hard to grasp how many influential innovations are rooted in the chemical sciences that have shaped our modern lives. In this essay, I will focus on three key examples that are of enormous importance for our society: Synthetic polymers (plastics) that can be found everywhere from household items to industry, energy storage materials like Li-ion batteries (LIBs) that are in every smartphone, electric vehicle or other pieces of modern technology and medicines that have helped us fight terrible diseases. But all these innovations come with a price.

The cost of invention

The Haber-Bosch process alone, which is based on thermal catalysis and requires high pressures (>100 bar) and temperatures (400-500 °C), consumes around 2% of the world's annual energy production. At the same time, the ammonia synthesis industry produces more than 670 Mt of CO_2 every year, corresponding to 2.5% of global greenhouse gas emissions.[2] Over 380 Mt of plastics are produced every year.[3] However, only a fraction of the world's plastic waste is recycled while the majority is incinerated, landfilled or leaked into the environment.[3,4] Plastics pollute our environment while microplastics penetrate almost every part of our planet and bodies.[3,5,6] The rising demand for lithium, due to the growing popularity of electric vehicles, makes it a critical resource whose extraction causes enormous environmental damage. The recycling of LIBs promises a circular economy, but their complete recycling is associated with challenges for which the industry is not yet sufficiently prepared.[7,8] The production of pharmaceuticals is one of the most waste-intensive areas of chemistry. In the pharmaceutical industry, producing one kg of product can generate up to 25-100 kg of waste.[9]

Even though chemistry has given us all these life-changing inventions, it is also one of the most energy-intensive industries and one of the largest producers of waste in the world.[10] It is therefore necessary to rethink chemistry. In the context of climate change and increasing pressure for greater sustainability, incremental changes will not be enough. We need to change the status quo of chemical sciences and implement new, disruptive approaches. When it comes to waste, the priority must be to avoid it completely. If it is unavoidable, it needs to be recycled and transformed into valuable products.

The scourge of chemistry

One systemic problem in the chemical sciences is the use of solvents. Solvents are ubiquitous in chemistry and their use in the past 200 years has been intertwined with the development of the chemical sciences.[11] Due to the associated risks for health, safety and the environment, as well as the sheer scale of solvent production each year, which represents one of the largest sources of waste in the chemical industry, the use of solvents is viewed increasingly critically since the advent of green chemistry.[12] The first principle of green chemistry states that prevention is the best form of waste treatment. Therefore, the most appealing approach to solvent waste is not to use solvents at all.

This raises the question of why solvents are so omnipresent in the chemical sciences. Solvents have several functions: They allow the mobility and diffusion of reactants, stabilization of transition states, certain selectivities and transport of thermal energy. But solvents are by no means a necessity. Reactions without solvents have been known for a long time and in recent years, alternative, solvent-free or solvent-minimizing approaches have received increasing attention in the context of growing awareness of sustainability and the need for greener chemical reactions and processes.[13–15]

Mechanochemistry: generating value by preventing and transforming waste

Mechanochemistry is one such alternative that enables reactions directly between solids without solvents or with only minute quantities. Mechanochemistry was identified as one of 10 world-changing chemistry innovations by IUPAC.[16] A mechanochemical reaction is the result of the action of mechanical forces. Instead of glassware, ball mills serve as reactors. Milling balls collide inside milling vessels with reactants at high frequencies, providing the necessary energy for the reaction, while simultaneously enabling mixing of the solid reaction mixture.[17–19] Additionally, mechanochemical reactions can also be scaled up, e.g. in flow via extrusion.[20–22] Mechanochemistry represents a disruptive platform technology with application potential in many areas of the chemical sciences while being in line with the principles of green chemistry and sustainable development goals.[23,24] While mechanochemistry has historically been used in inorganic chemistry,[25,26] its potential has been recognized in fields such as organic synthesis,[27] materials science[28] or medicinal chemistry.[29,30]

In the production of active pharmaceutical ingredients (APIs) solvents often account for 80-90% of the total mass of a reaction.[9,31] On an industrial scale, this generates gargantuan amounts of waste. In 2008, the US pharmaceutical industry generated 88 million kg of waste. 83% of this waste was attributed to only 10 solvents.[32] Furthermore, many of these solvents are toxic or otherwise harmful, and a growing number of them are being restricted. The latest prominent example is methylene chloride, which was largely banned under the Biden-Harris administration in 2024. This regulatory pressure puts additional stress on the pharmaceutical industry and forces change. To date, a large number of APIs have been synthesized using mechanochemical methods, which significantly reduce the use of solvents and make these processes safer and often faster than their solution counterparts. For example, the mechanochemical synthesis of paracetamol, one of the world's top-selling drugs, not only leads to higher yields but also outperforms the reaction in solution in several green chemistry metrics and halves the amount of produced waste.[33] Furthermore, due to its solid-state approach, mechanochemistry can be used for the solid-form screening of APIs, which is of great importance in the pharmaceutical industry.[29,30,34]

Beyond mere prevention, mechanochemistry is able to convert various waste streams into valuable products. Two important examples of this are the synthetic polymers and LIBs mentioned above. The outstanding properties of plastics, such as chemical and physical stability, that make them so useful make them also very durable, which leads to recycling challenges. It has been shown that mechanochemical depolymerization reactions can be highly efficient in converting plastic waste.[35] For example, polyethylene terephthalate (PET) and polystyrene (PS), which are used in a wide range of applications from packaging to textiles, can be converted into their valuable monomers using mechanochemical processes at ambient temperatures and pressures.[36,37] Even extremely inert and persistent polymers such as Per- and polyfluoroalkyl substances (PFAS) can be broken down using mechanochemistry.[38] As with polymers, mechanochemistry has also proven beneficial in the recycling of lithium-ion batteries (LIBs), whose conventional recycling processes require high temperatures, large amounts of energy and strong acids while generating emissions and waste and losing significant amounts of lithium during processing.[7,8] It has been shown that mechanochemistry can be used as a simple and universal approach for the recycling of different cathode materials with high metal yields at moderate temperatures and offers a sustainable alternative to conventional pyrometallurgical and hydrometallurgical approaches for the conversion of spent LIBs into their valuable components.[7,39,40]

Pharmaceuticals, polymers and LIBs are just some examples of important chemical products where mechanochemistry could lead to a paradigm shift. This list could be continued with further examples such as the valorisation of CO_2 or biomass.[41,42] However, mechanochemistry not only solves fundamental problems such as the ubiquitous use of solvents and offers a new method for converting waste into valuable products, but also enables new reactivities with huge potential for greater sustainability.[18] These include new forms of catalysis or the direct activation of solids such as metals or the mineral fluorite, which makes it possible to avoid dangerous hydrofluoric acid in the synthesis of fluorine-containing drugs.[43–46] And even for the Haber-Bosch process, mechanochemical approaches have been described in recent years, the results of which indicate that ammonia could be produced much more energy-efficiently with the aid of mechanochemistry, as the high temperatures (400-500 °C) and pressures (>100 bar) could be reduced to only 45 °C and 1 bar while achieving a higher final ammonia concentration than state-of-the-art processes.[47–49]

In summary, chemistry must reinvent itself in the context of climate change, environmental pollution and resource scarcity. This necessitates new and disruptive approaches such as mechanochemistry which can be applied across the breadth of chemical sciences and allows the prevention of solvent waste as well as the transformation of other waste streams such as polymers or spent LIBs into valuable products. In addition, mechanochemistry allows reactivities previously thought impossible, making new reaction pathways accessible and avoiding hazardous waste while processes are faster and require less energy.

Statement on use of AI

AI was used in the preparation of this essay for language editing and to improve clarity and readability. No AI tool was used to generate original scientific insights, interpret data, or draw scientific conclusions.

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Finalist

The tale of CO_2: source, impact and solution

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Consumption continues to rise with the growing global population, particularly in wealthier nations. According to a report in the *Los Angeles Times*, the average American household owns approximately 300,000 items.[1] Most of these products have a common starting material: fossil fuels. While consumers often focus on the final product and, at times, the raw materials, few consider the processes that drive these transformations. Yet, these are the very processes that release significant amounts of greenhouse gases such as CO_2.

As consumption has surged, so have greenhouse gas emissions. The global CO_2 emission has skyrocketed from 9.3 million tonnes in 1750 to a staggering 37.8 billion tonnes in 2023, leading to a temperature increase of 1.2 °C from pre-industrial times.[2] To mitigate this crisis, two critical actions are necessary: (1) reducing dependence on fossil fuels and (2) actively lowering atmospheric CO_2 levels.

The 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015, identifies 17 Sustainable Development Goals (SDGs).[3,4] To achieve these goals, seven key initiatives are crucial: Infrastructure Imperatives, Carbon Management, Green Energy, Circular Economy, Environment Conservation, Water Conservation, and Energy Efficiency. Carbon Capture, Utilisation, and Storage (CCUS) technologies can play a vital role in reducing GHG emissions by capturing and converting CO_2 into valuable products, thereby promoting sustainable development.[5]

The balance between emissions and removals determines the concentration of CO2 in the atmosphere. Carbon dioxide removal (CDR) focuses on extracting CO_2 that has already been accumulated in the atmosphere. In contrast, carbon capture intercepts CO_2 at its source, such as industrial waste gas streams, before it is released. In essence, carbon capture prevents new emissions, whereas CDR works to reverse past emissions. Utilization offers a sustainable alternative by converting captured CO_2 into valuable products, such as synthetic fuels and chemicals, reducing reliance on fossil carbon.

According to the IPCC, CDR is essential for addressing emissions from sectors that are particularly difficult to decarbonize. Estimates suggest that removing 100 to 1,000 gigatonnes (Gt) of CO_2 will be necessary throughout the 21st century to limit global warming to less than 1.5°C.[6] To put this into perspective, by 2100, we may need to remove up to 15 Gt of CO_2 annually. Nature already performs CDR through photosynthesis, but large-scale reforestation efforts can disrupt natural ecosystems. Planting forests in regions that historically lacked tree cover, such as grasslands and savannas, can lead to habitat destruction and a significant loss of biodiversity.[7]

Another approach for CDR from the atmosphere is geological storage. It involves compressing gaseous CO_2 until it reaches a supercritical state, then injecting it into deep underground reservoirs of porous rock (empty oil wells), where it should remain indefinitely. Supercritical CO_2, formed under high pressure, combines liquid-like density with gas-like flow, enabling efficient underground storage. To remain in its supercritical state, CO_2 must be subjected to extremely high-pressure conditions; that's why it must be stored very deep (typically around 1 km) underground beneath an impermeable layer to prevent it from leaking back into the atmosphere. Over time, CO_2 can react with minerals, forming stable carbonates through mineral trapping, ensuring long-term sequestration and reducing atmospheric release risks. Global underground CO_2 storage capacity ranges from 6,000 to 25,000 Gt, enough to manage excess emissions. Stored CO_2 can remain stable if reservoirs are well-managed, with a study showing a 98% retention rate over 10,000 years.[8]

Another way of storing CO_2 is in the oceanic sink, which has a global capacity of 1,000 Gt. But this poses risks to marine life by altering the acidity and local chemistry of the ocean. Unlike geological storage, ocean CO_2 release occurs over hundreds of years. Given its environmental impact and the availability of safer alternatives, large-scale ocean storage is not a viable solution.

Various strategies are being explored for CO_2 capture, including physical and chemical absorption, adsorption, cryogenic, and membrane separation technologies. Among them, chemical absorption using amine solutions is the most common method for large-scale industrial applications. Amines reversibly bind with CO_2, allowing efficient capture and release under the right conditions. At RT, CO_2 (in fuel gas) can react with amines to form carbamates and bicarbonates, and at a higher temperature (~100°C), these bonds are broken, releasing purified CO_2. There are several challenges, such as energy consumption required for achieving higher temperatures and solvent degradation. Ongoing research aims to develop alternative materials and processes that enhance efficiency while reducing environmental and economic costs. Potential solutions include utilizing sunlight in the second chamber to facilitate CO_2 release instead of high-temperature furnaces and exploring solid sorbents like zeolites, MOFs, and COFs for improved adsorption-based capture.[9,10]

According to thermodynamics, capturing CO_2 requires less energy at higher concentrations. This makes point sources like power plants and refineries more efficient for carbon capture than direct air capture. However, challenges remain, such as fluctuating flue gas composition and high flow rates, which complicate the extraction of pure CO_2. One approach for capturing CO_2 from more dilute sources involves exposing large volumes of air to hydroxide-rich solutions, which react with CO_2 to form carbonates. However, the high solubility of these carbonates makes separation challenging. To overcome this, a second step involves reacting the carbonate with $Ca(OH)_2$ to form solid $CaCO_3$, which can then be thermally decomposed at approximately 700°C to release purified CO_2. While effective, this process is energy-intensive, highlighting the need for more efficient direct air capture technologies.[11]

Catalysis plays a crucial role in CO_2 utilization, enabling its conversion into valuable products. Various catalytic approaches exist, as illustrated in **Figure 1**, each categorized based on the type of energy input used. These include thermal, electrochemical, and photochemical catalysis, among others. Since energy can be interconverted between different forms, the ultimate goal is to harness renewable sources, particularly sunlight, to drive these reactions.

The conversion of fossil resources like coal and natural gas into liquid fuels occurs at high temperatures to produce syngas (a mixture of CO and H_2). This syngas is then transformed into liquid hydrocarbons through the Fischer-Tropsch process. Similarly, methanol, a key industrial feedstock used in the production of about 30% of chemicals, is traditionally synthesized from syngas. A major step toward sustainability would be replacing syngas derived from fossil fuels with CO_2 from atmospheric or waste sources, enabling a more carbon-neutral methanol economy.[12]

Beyond fuels and chemicals, CO_2 is also utilized in fertilizer production. Urea, a nitrogen-based fertilizer, is synthesized from ammonia (NH_3) and CO_2 via the Bosch-Meiser process. However, this method requires high temperatures and pressures, making it energy-intensive and reliant on fossil-derived CO_2, contributing to a significant carbon footprint. Developing a single-step, low-energy alternative would improve efficiency and sustainability.

CO_2 utilization can be extended to industries like plastics, cement, and steel manufacturing. Innovations in CO_2-based polymerization offer pathways to sustainable plastics,[13] while mineralization techniques can incorporate CO_2 into cement,[14] and CO_2 can replace carbon-based reductants in steelmaking. By integrating CO_2 as a feedstock in multiple sectors, we can transition toward a circular carbon economy and reduce reliance on fossil fuels.

While various catalytic processes can convert CO_2 into valuable chemicals and fuels, one critical component is still missing: hydrogen. To replace fossil hydrocarbons, we need alternative sources of both carbon and hydrogen. Though hydrogen is a promising energy carrier, 96% of its global supply still comes from fossil fuels, primarily through steam methane reforming, which releases CO_2. Technologies for direct solar-driven splitting of water and solar thermal distillation have to be developed, though improving energy efficiency remains key. The challenge here is to maximize hydrogen production while minimizing environmental and economic costs.

Achieving a sustainable, emissions-free economy requires the large-scale integration of CO_2 capture, storage, utilization, hydrogen production, renewable energy harvesting, and energy storage technologies. Minimizing material and energy consumption is essential for sustainability, along with ensuring that any heat or electricity used comes from renewable sources. Additionally, the carbon footprint of energy and material inputs must be carefully considered. Increased government support for research can accelerate advancements in carbon capture, storage, and utilization, making these technologies more efficient and economically viable.

In conclusion, I would like to say that change is underway, but the energy transition must be accelerated to stay below the tipping point of carbon-driven climate change. Achieving a sustainable and equitable future will require deep systemic shifts in our economic structures. It is a daunting challenge, but as a shared world, we must collectively take on the immense responsibility of protecting the Earth and securing our future with the same care we give ourselves.

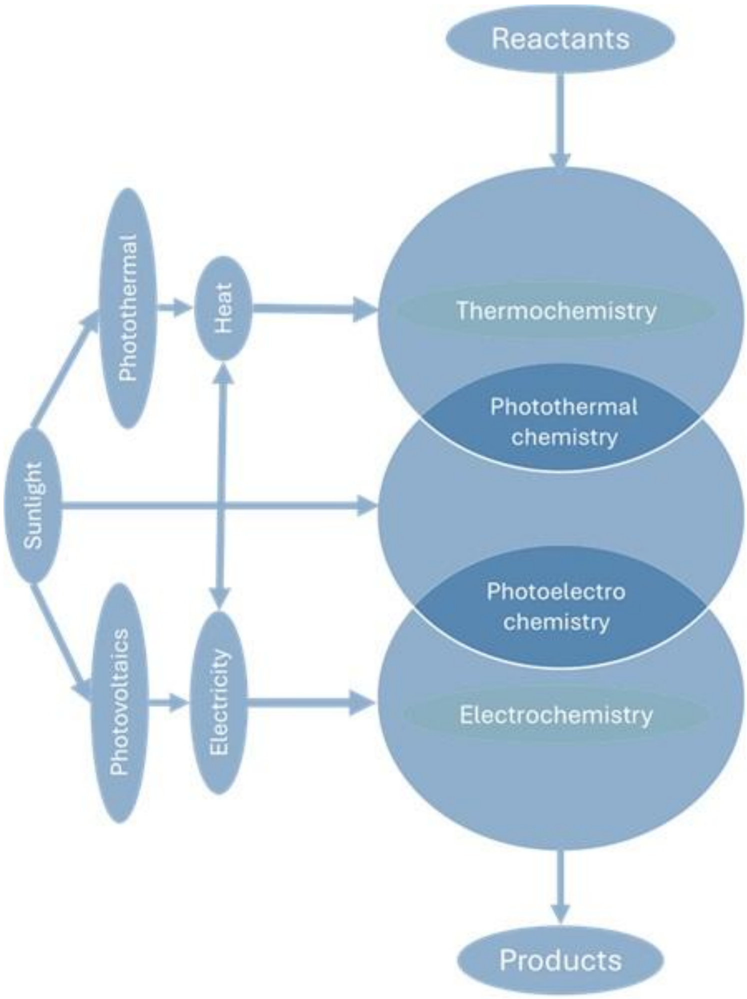

Figure 1 Various processes in catalysis with sunlight as primary source of energy

Statement on use of AI

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Finalist

Reimagining waste as an opportunity: how chemical sciences are powering the future using nuclear byproducts

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As industrialization and economic advancement accelerate, so does the generation of waste, posing severe environmental threats and escalating resource depletion. From plastic pollution choking marine ecosystems to industrial byproducts contaminating land and water, the consequences of unchecked waste disposal are alarming. As global priorities shift toward sustainability, it is imperative to shift from a linear economy of "take, make, dispose" to a circular model where waste is repurposed into valuable resources.[1] Chemical sciences play a pivotal role in this transformation, offering innovative approaches to convert waste into fuels, chemicals, and advanced value-added materials, thereby reducing environmental footprints while fostering economic growth. By leveraging green chemistry, catalytic processes, and biotechnological advancements, we can mitigate waste accumulation and build a future where industrial byproducts are not pollutants but valuable assets.

Among the most intriguing and paradoxical types of waste is radioactive waste. Every year, the world produces thousands of tonnes of high-level radioactive waste-a material often feared, seldom utilized, and destined to be buried for millennia. At the same time, we face a mounting energy crisis: a growing demand for sustainable, long-lasting power in remote, off-grid, and extreme environments. What if one problem could help solve the other?

In this quest for alternative sustainable solutions, radioactive waste-powered batteries have emerged as a transformative innovation that exemplifies how chemical science can redefine waste as a resource, and fear as opportunity. This essay explores how chemistry is turning long-lived nuclear byproducts into durable energy sources, what this means for sustainability, and why bold scientific thinking is pivotal to a greener future.

The dual crisis of nuclear waste disposal and clean energy transition is deeply intertwined. The International Atomic Energy Agency (IAEA) estimates that over 250,000 tonnes of high-level radioactive waste are stored globally-material that remains hazardous over a long span and poses complex environmental and ethical challenges.[2] According to the World Nuclear Association, the IAEA estimates that approximately 392,000 tonnes of heavy metal (tHM) in the form of used nuclear fuel have been discharged since the inception of nuclear power plants. This used fuel is considered high-level waste due to its significant radioactivity.[3] Meanwhile, the global demand for clean, reliable energy is rising, especially in isolated locations such as space missions, deep-sea sensors, medical implants, or disaster zones, where conventional batteries fall short due to curtailed lifespans.

Over the years, significant global attention has been diverted to the meticulous strategic disposal of radioactive byproducts. In this context, India has embraced the transformative outlook towards resource recovery from radioactive materials through a closed fuel cycle approach. This strategy emphasizes reprocessing spent nuclear fuel to recover and recycle fissile materials, thereby minimizing waste and maximizing resource utilization.[4] The Bhabha Atomic Research Centre (BARC) has been at the forefront of these initiatives. BARC has developed advanced techniques to extract useful radionuclides from high-level radioactive waste. Notably, radionuclides such as Cesium-137, Strontium-90, and Ruthenium-106 have been recovered and repurposed for various societal applications.[5] A significant achievement by Indian nuclear scientists is the extraction of a rare form of radioactive caesium from nuclear waste. This extracted caesium is utilized in blood irradiation to sterilize blood, enhancing medical safety.[6] The IAEA has recognized and commended this breakthrough. These endeavours underscore India's commitment to innovative nuclear waste management practices that prioritize environmental safety while harnessing the latent value within nuclear by-products.

While these processes are promising, the innate human drive for innovation and curiosity has led researchers to explore even more radical avenues, one of which is the concept of "power from poison." With this, the fundamental idea of radioactive-waste-generated batteries has taken shape. Unlike renewable sources like solar and wind, which are intermittent, and lithium-ion batteries that degrade over time,[7] a new class of batteries called nuclear or betavoltaic batteries promise continuous, low-maintenance energy by exploiting the intrinsic decay of radioactive isotopes.[8] At the heart of these batteries lies a unique form of electrochemistry, which brings forth the remarkable transformation of radioactive decay into usable electricity. Betavoltaic devices work by using beta particles (high-energy electrons emitted during radioactive decay) to generate electricity. One promising design involves using carbon-14, a radioactive isotope extracted from graphite blocks used in nuclear reactors embedded within a synthetic diamond layer. The diamond acts as both a radiation shield and semiconductor, converting energy from decay into usable electric current. This structure is chemically stable, durable, and able to function for decades or even centuries without the need for recharging or replacement. Another emerging innovation involves incorporating nanomaterials which can significantly boost electron-hole pair generation and current output, potentially unlocking broader renewable energy and decarbonization applications. The key innovation is not only in the electrical engineering but also in the chemical transformation of dangerous waste into a stable, functional material. This process involves extracting carbon-14 from irradiated graphite, which requires specialized chemical processing; synthesizing diamond-like carbon using chemical vapor deposition (CVD); and engineering semiconducting materials that can withstand constant radiation without degradation. Dr. Tom Scott, Professor of Materials at the University of Bristol, has been instrumental in reporting this novel concept of the 'diamond battery,' and his group continues to generate advanced prototypes of this technology.[9] This innovative battery utilizes carbon-14, with a half-life of 5,700 years, rooted within a synthetic diamond structure to generate electricity as the isotope undergoes beta decay. The radiation interacts with the diamond, producing a continuous electric current. Due to carbon-14's extended half-life, such a battery could theoretically power devices for millennia.[10]

This technology holds immense prospects for real-time implementation requiring long-lasting, low-maintenance power sources, such as medical implants (e.g., pacemakers), space exploration vehicles, and remote sensing devices.[11] In comparison to conventional batteries that often require regular replacement and contribute to electronic waste, these nuclear batteries offer a revolutionary leap in sustainability and functionality.

Moreover, batteries powered by radioactive waste align remarkably well with multiple United Nations Sustainable Development Goals (SDGs). They provide continuous, clean electricity without emissions or moving parts, aligning with SDG Goal 7: Affordable and Clean Energy.[12] By converting hazardous waste into valuable products, they embody the circular economy principles under Goal 12: Responsible Consumption and Production.[13] Additionally, by reducing the demand for short-lifespan batteries and supporting renewable systems with backup power, they significantly contribute to Goal 13: Climate Action.[14]

Despite their promise, challenges remain. These batteries currently produce low electrical currents, suitable only for small devices. Scaling them for high-power applications such as electric vehicles or home energy storage remains a major hurdle.[8] Additionally, synthetic diamonds and isotope processing are currently expensive, though costs may decrease with technological advancements and economies of scale.[15] Social stigma and public fear associated with anything radioactive also pose obstacles. Therefore, strong science communication and education are crucial for shifting public perception and garnering support for such innovations.[16]

Furthermore, legal and ethical considerations must be addressed. The handling, transportation, and disposal of radioactive materials are tightly regulated, and these batteries must adhere to strict international safety protocols.[17] There is a need for global coordination to ensure safe and ethical deployment. Policymakers must work in tandem with scientists to create comprehensive regulatory frameworks that prioritize safety without stifling innovation. This emerging technology also exemplifies the deep intersections between science, society, and policy. The chemistry behind nuclear batteries may be complex, but its societal implications are profound. Scientists must not only develop these technologies but also communicate their benefits clearly, counter misinformation, and collaborate with policymakers and ethicists to ensure responsible innovation. Countries with significant nuclear capabilities, such as the UK, USA, France, Russia, and India, have a responsibility and an opportunity to take the forefront in designing resilient, collaborative systems for nuclear waste mitigation.[18] International frameworks, potentially under the IAEA or United Nations, could facilitate research sharing, safety standardization, and scaled deployment in regions with limited access to reliable electricity. In addition, the future of radioactive-waste-based energy solutions depends on interdisciplinary collaboration. Chemists, physicists, materials scientists, engineers, policymakers, and social scientists must come together to navigate the technical, societal, and ethical complexities of such groundbreaking innovation. Universities and research institutions have a critical role to play in fostering this collaborative ecosystem, as do industries willing to invest in long-term, high-impact solutions.

At first glance, the idea of building batteries from radioactive waste might sound counterintuitive, even dangerous. Yet this innovation captures the very essence of sustainable chemistry: turning problems into solutions. By reimagining nuclear waste as a resource, chemical science is tackling both the intersecting crises of environmental decline and energy scarcity, while reshaping our fundamental approach to sustainability. The future of energy may not rest solely in the sun or wind, but also in the creative potential of decay. As we stand at the crossroads of ecological crisis and scientific opportunity, it is imperative to support and invest in chemical sciences that offer not just alternatives, but visionary breakthroughs. Radioactive-waste-powered batteries are not just a scientific curiosity; they are a testament to human ingenuity and a beacon of what is possible when chemistry meets courage.

What was once a threat buried beneath our feet might soon be lighting the path ahead.

Statement on use of AI

No AI was used in the generating idea of the essay. The writing plan, structured flow, and scientific content are entirely the author's original work.

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Finalist

Alchemy or chemistry? Turning waste into valuable resources for humanity through scientific innovation

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Introduction

Have you ever wondered if the trash we throw away could become tomorrow's treasure? Although it might sound like science fiction, it is not a new idea. Many centuries ago, alchemists believed that ordinary metals, such as lead or mercury, could be transformed into valuable ones such as gold or silver through the so-called "Philosopher Stone". They spent centuries performing experiments with "magical" substances and using "secret formulas" to achieve their goal, although they never succeeded. However, their work laid the foundations of modern chemistry and materials science, as they developed techniques such as distillation, sublimation, filtration, and crystallization, to name a few, that have subsequently been refined to the present day.[1] Arguably, the alchemists pioneered the idea that the most unlikely materials can harbour untapped potential.

The concept of transforming basic materials into something valuable has evolved over time and today it is a topic that has captured the attention of our government leaders. With millions of tons of waste disposed of every year, landfills run out of space, resources are depleted to unsustainable levels, and ecosystems are becoming increasingly polluted. It is therefore urgent to take immediate action to tackle this problem, as the increase and accumulation of waste not only threatens the availability of resources and biodiversity but also accelerates climate change. Turning waste materials into valuable resources for humanity is a way to address this situation and aligns well with one of the United Nations' Sustainable Development Goals to be achieved by 2030. Specifically, goal number twelve draws attention to responsible consumption and production, aiming to reduce waste generation through prevention, reduction, recycling, and reuse,[2] with the ultimate goal of transitioning towards a circular economy.

Different types of waste hold the potential to be transformed into valuable resources, including but not limited to organic, industrial, electronic, plastic, and hazardous waste. Of these, organic waste is one of the most abundant. Through the application of advanced chemistry, the revalorisation of food waste components – whether generated from human consumption or industrial processes – can enable their conversion into a wide range of valuable products such, as chemicals, biofuels, and innovative materials.[3]

One example of this revalorisation could be the transformation of dairy waste (cheese whey) into advanced materials through bottom-up chemical approaches, which involve building materials from smaller components, such as solvothermal methods, microwave-assisted techniques, or pyrolysis. Whey, formed mostly by lactose and proteins, is a significant by-product generated in large amounts by the dairy industry during cheese production, as to produce one kilogram of cheese from milk, approximately nine litres of whey are generated. If not properly managed and disposed of as wastewater, it can become a serious environmental pollutant due to its high content in organic matter, which significantly increases the biochemical oxygen demand.[4-6] As a result of the growth of microorganisms consuming these organic substances, oxygen from the water is depleted, leading to the death of aquatic life.[5,7] Thus, it is necessary to find a way to reuse this waste material. Some of the proposed uses include the production of biogas through anaerobic digestion and the elaboration of whey powder protein.[8] More recently, it has been suggested that whey could serve as a raw material for the synthesis of carbon dots, which hold great potential for applications in the fields of optoelectronics and biomedicine, due to their bright and tuneable luminescence, high resistance to photobleaching and high biocompatibility.[9-10] Moreover, carbon dots can be synthesized from other types of organic waste, such as fruits, vegetables, and plants, thus increasing the number of substances that can be used as starting materials. Also, they are promising alternatives to traditional semiconductor quantum dots, which rely on more toxic compounds.[11]

Another growing type of waste in increasingly hyper-connected and technology-dependent societies, like ours, is e-waste, including items such as cell phones, laptops, household devices, and even solar panels. This kind of materials are composed of noble and transition metals such as gold, silver, or copper, as well as rare-earth elements, which can be difficult to obtain due to their limited geographic distribution and the challenging processes involved in their extraction and refining. Thus, reusing these elements is of utmost importance to guarantee their supply. Some of the employed methods to recycle e-waste and recover metals include, among others, chemical or biochemical processes, such as pyrometallurgy, hydrometallurgy, and biometallurgy, to name a few. Pyrometallurgy involves the use of heat treatments at elevated temperatures to separate metals from the material. However, although it is effective in the recovery of many metals, toxic gases can be produced during the process. Thus, more eco-friendly methods are desirable. On the other hand, hydrometallurgy relies on the use of aqueous solutions, generally acids or bases, to separate metals through chemical reactions. Although it is a sustainable approach, it still relies on the use of harsh solvents.[12] Recently, it has been demonstrated that the use of ionic liquids, particularly deep eutectic solvents, in metal extraction (ionometallurgy) holds great potential for metal recovery. These solvents offer the advantage of being environmentally friendly, recyclable, and reusable, putting into practice the principles of green chemistry.[13] Biometallurgy, on the other hand, employs microorganisms to leach metals from ores or waste materials. Through all these techniques, elements such as Au, Ag, Cu, Mn, Zn, Co, In, and Al, can be recovered.

Despite the great potential of chemical sciences in the revalorisation of waste, several challenges must be addressed before we can take advantage of its benefits. Firstly, governments and private sector organizations should prioritize investing in the development of recycling technologies and infrastructure to efficiently collect, process, and transform waste materials into valuable feedstock. Collaborations with the academic community are also crucial for the successful implementation of these initiatives. Examples of needed investments should include increased research funding and the creation of incentives to encourage businesses to adopt the newly developed technologies. Secondly, governments must establish a favourable regulatory framework that encourages the use of waste as feedstock. This could comprehend the creation of tax incentives, subsidies, and the simplification and streamlining of permitting licenses. Nonetheless, these measures alone are not sufficient if the greater public is not aware of the benefits of recycling, upcycling, and reusing. Creating a sustainable future requires collective action and people's commitment plays a key role in this. Education and awareness campaigns, as well as community-driven initiatives (e.g., workshops, local recycling centres, etc.), are essential to achieve this goal.[14] By working together -governments, researchers, private entities, and society as a whole- we can build a more sustainable and prosperous future, not only for our planet but also for each of us.

In closing, the use of chemistry as a tool to sustainably transform waste materials into valuable products for humanity holds great potential to tackle today's environmental challenges. Through diverse chemical processes, waste can be converted into innovative materials and metals can be recovered from discarded electronic devices. These are just a couple of examples of the many possibilities that the chemical sciences offer for the revalorisation of waste. However, science alone is not enough to move towards a more sustainable future. Just as every chemical reaction requires the right conditions to proceed, the prosperity of our planet also relies on humanity making the right choices and working collectively to maintain the adequate balance necessary for its sustainability. We must not forget that, as was said on World Environment Day 2022, "In the universe there are billions of galaxies, in our galaxy there are billions of planets, but there is only one Earth. Let's take care of it".[15] Keep in mind: there is no planet B. The choices we make today will determine the world of tomorrow.

Statement on use of AI

AI, specifically ChatGPT and Copilot, was used in the preparation of this essay only to improve its readability and language. After using these tools, the author reviewed and edited the content.

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Finalist

Chemistry for circular economy: "reaction parameters" to transform waste into opportunity

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"*Nothing is lost, nothing is created, everything is transformed.*" With this timeless principle, Antoine Lavoisier laid the foundation of modern chemistry and offered a parallelism for today's sustainability challenges. His words remind us that, like reactants in chemical reactions, waste does not simply vanish, but it is inevitably transformed. The question is how. Will we let it turn into pollution, or can we guide the reaction toward creating something valuable?

Today, in the Anthropocene, a period defined by humanity's impact on the planet, we are surrounded by the "*reactants*" of our own making: plastic debris, industrial emissions, and growing landfills.[1] These by-products of human activity are already in motion, transforming, and harming global ecosystems. But just like a chemist adjusts temperature, pressure, or catalysts to steer a reaction, we too can recalibrate the "*reaction parameters*" of our system to shift the outcome from environmental harm to sustainable wealth.

This is where chemical sciences play a vital role. By applying innovative technologies, we can transform waste into raw materials, emissions into energy, and environmental threats into opportunities. However, shifting from a linear, wasteful economy to a circular one requires more than scientific advances alone. As with any chemical reaction, multiple factors must align: scientific innovation, technological feasibility, policies and collaborative frameworks, and cultural values. One of the greatest challenges for chemical science in delivering transformative solutions lies in bringing these diverse "*reaction parameters*" together.

Developing technologies to redefine waste material into something valuable is no easy task but thanks to chemists' vision, every molecule becomes an opportunity. The first challenge is to address the heterogeneity of waste streams, which requires targeted and flexible approaches. Among these streams, a significant portion is biowaste, comprising approximately 45% of global solid waste.[2] This category represents a hidden reservoir of molecules with diverse functional, nutritional, and structural properties, that can be extracted and directed toward tailored applications. Agro-forestry residues, including pomace, peels, seeds, and pruning waste, are rich sources of high-value compounds such as polyphenols, pectins, proteins, and essential oils.[3] These molecules possess functional, preservative, and health-promoting properties, making them valuable in food, pharmaceutical, and cosmetic sectors. Collectively, these products represent a substantial economic potential, with markets valued in the billions, projecting significant growth and investment opportunities.[4] Advanced extraction technologies are critical to unlocking this potential, and improving yield, selectivity, and environmental performance.[5] Following the recovery of high-value molecules, the residual lignocellulosic biomass can be converted through mechanical, chemical, or biochemical processes into biofuels, platform chemicals, or biochar.[6,7] This cascading valorisation approach sustains integrated biorefinery models, which are central to implementing zero-waste strategies in circular economy systems.[8] In addition to plant-based residues, animal by-products from land and marine biomass, such as bones, feathers, shells, and fish viscera, also represent potential resources. Extractable proteins such as collagen, gelatin, and keratin and structural carbohydrates like chitin, have wide-ranging applications in bioplastics, biomedical devices, and advanced materials, further expanding the spectrum of biowaste chemical transformation to bio-based products.[9,10]

Beyond organic residues, modern societies generate increasingly complex waste streams, including plastic, composite materials, and electronic waste (e-waste). E-waste is currently one of the fastest-growing and challenging types of residues.[11] However, despite its complexity, advancements in chemical processing technologies have made it possible to recover valuable materials also from it. For example, the leaching process applied to black mass from spent lithium-ion batteries yields precious metals such as nickel, cobalt, manganese, and lithium, while the remaining graphite-rich fraction can be purified and reused.[12,13] As mentioned, the heterogeneity of waste is enormous, but fortunately, the scientific literature offers a wide range of valorisation strategies for even the most unexpected materials. A striking example comes from used baby diapers, a significant contributor to municipal solid waste. Recent studies have shown that nanocellulose can be obtained from diapers providing high-purity products for biopolymers with advanced material applications.[14] Overall, these cases demonstrate that, ideally, no waste is too complex to be valorised. With the right chemical approaches, everything from agricultural residues to e-waste, and even diapers, can become a resource.

Transforming waste technologies holds potential, though ensuring that these processes are both safe and sustainable remains a central issue. Guided by the principles of green chemistry, green engineering, and green extraction, emerging "*benign-by-design*" protocols arise to replace conventional methods with greener and safer alternatives.[15-17] Several enabling technologies already reflect this shift, including ultrasonic and hydrodynamic cavitation, microwave-assisted processing, ohmic heating, pulsed electric fields (PEF), and more experimental photo-electro-mechanochemistry techniques.[18,19] Together with the adoption of alternative green solvents such as pressurized fluids, natural deep eutectic solvents (NADES), ionic liquids, and 2-methyltetrahydrofuran (2-MeTHF), these innovations are paving the way for more efficient and environmentally benign processes.[20] However, despite promising laboratory-scale advancements, the transition from research to industry is still often limited by low technological readiness levels.[21] Systems such as PEF and cavitation reactors, subcritical water extraction, and 2-MeTHF based processes have shown feasibility at the semi-industrial level, demonstrating process stability, energy efficiency, and product quality under scaled-up conditions.[22-25] Nonetheless, further development is required before they can be fully implemented in commercial settings.

Advancing research innovations to market deployment requires comprehensive assessments to ensure sustainability and industrial viability. This includes analysing environmental impacts, energy use, hazardousness, waste generation, and economic factors such as cost, yield, and product quality. Techno-Economic Assessment (TEA) and Life Cycle Assessment (LCA) are key tools in this regard. TEA focuses on technical feasibility and cost-effectiveness, while LCA provides a comprehensive view of environmental impacts across the entire life cycle.[26,27] Addressing both economic and environmental objectives is essential but introduces significant complexity to process development. To navigate this, digitalization is playing a pivotal role.[28] Like other industries, the chemical industry is becoming increasingly smart, connected and data-driven.[29] Artificial intelligence (AI) and the Internet of Things (IoT) are revolutionizing process monitoring, control and optimization.[30] The integration of sensor-based systems enables real-time feedback and autonomous control, contributing to safer and more responsive chemical production. In this perspective, the integration of an Industry 4.0 framework serves as a strategic enabler for aligning environmental, economic, and operational objectives in chemical process design.

The technology industrialization can be further catalysed by a synergistic collaboration between universities, companies, and institutions. Companies drive innovation needs, universities serve as research incubators to develop and refine solutions, and together, through partnerships and shared investments, they can bring scalable and market-ready technologies to life. At the institutional level, the European Union plays a pivotal role through initiatives such as the European Green Deal, and the First Circular Economy Action Plan. [31, 32] Together, these strategic policies, provide legal and financial incentives to accelerate the development and market adoption of scalable, circular, and sustainable technologies.

Within this complex system, effective communication is also essential. It fosters cultural values that align the efforts of all stakeholders toward sustainability. Initiatives such as the establishment of the Nine Planetary Boundaries framework, the "*Earth Overshoot Day*", and the Sustainable Development Goals (SDGs) serve as powerful tools to visualize environmental limits and sustainability objectives.[33-35] Among the SDGs, Goal 17 highlights international collaboration as essential for achieving sustainability, particularly in addressing global challenges like waste management. Waste is a shared issue that requires holistic, inclusive solutions. Even if high-income countries adopt circular practices and reduce pollution, emissions and waste from less-resourced regions still impact global ecosystems. Local improvements alone are not enough. Advancing sustainability demands global cooperation, equitable innovation, and inclusive policies that empower all countries to participate in building a cleaner, more resilient and interconnected future. Efforts such as the Basel Convention, United Nations Industrial Development Organization (UNIDO) circular economy programs, Global Environment Facility (GEF) initiatives, and the Africa Circular Economy Alliance are important steps toward this goal, yet barriers in financing, scalability, and local adaptation persist.[36-39]

As Paul Romer's theory of Endogenous Technological Change asserts, innovation arises when research, knowledge sharing, and supportive policies converge; conditions increasingly present today.[40] A successful model is the Kalundborg Symbiosis in Denmark, where industrial actors have established a collaborative circular system through the exchange of energy, water, and materials.[41] Such initiatives demonstrate the potential of circular approaches when key enabling factors are in place. The pressing task now is to convert this demonstrated potential into scalable and broadly implemented practice.

In conclusion, while chemical science is essential to transforming waste into wealth, it is only the first building block. Lavoisier's principle, "*everything is transformed*," was meant to describe the behaviour of matter, but we can also read it as an invitation to rethink and reshape our societies and economic models. If our current systems are no longer sustainable, they must be transformed too. A transformation in which each "*reaction parameters*" play a role; scientific innovation as the main reaction mechanism that enables new solutions, technological feasibility as the tuneable parameters to unlock scalability, collaborative frameworks as the catalyst that drives systemic change, and cultural values as the activation energy that lowers barriers to adoption. Transformation is inevitable, but its direction depends on how we set the system's conditions. The time to adjust the reaction is now.

Statement on use of AI

AI was used in the preparation of this essay for improve readability and language of the work.

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Finalist

A dual waste valorisation approach to effective mitigation of plastic pollution

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Plastic pollution has emerged as a monumental global challenge. About 425 million metric tons of plastic waste are produced annually and this number continues to grow steadily.[1] Moreover, microplastics and nanoplastics are pervasive, found in almost everywhere on Earth from soil and air to human organs.[2] We now know that the plastics are inert and hardly degradable, but we hardly know about their actual toxicity and detrimental effects. Therefore, ultimate solutions to mitigate plastic pollution are in urgent need, which can only be achieved with the aid of the chemical sciences and related efforts in academia, industry, and society.

A non-biodegradable nature of conventional plastics serves as a fundamental origin of plastic pollution. Furthermore, current petroleum-based plastic production routes produce greenhouse gases, which impedes carbon neutrality goals.[3] Therefore, a dual approach is essential to resolve current plastic pollution which includes: (i) utilization of waste biomass for fabricating biodegradable plastics, and (ii) recycling and upcycling of non-degradable plastic waste to produce monomers and valuable chemicals (**Figure 1**). Chemical sciences indeed play a pivotal role in both approaches. The most interesting aspect is that the both approaches can effectively harness waste resources, ultimately dealing with multiple environmental issues including waste pollution and greenhouse gas emissions.

Figure 1 A dual approach to plastic waste solution
(Original figure components obtained from Flaticon with permission and modified using Adobe Illustrator)

Utilization of waste biomass for fabricating biodegradable plastics

We generate considerable amounts of organic waste daily, including agricultural waste, food loss and waste, industrial waste, algal bloom, and others.[4-6] It is worth emphasizing that various natural polymers consisting of organic matters provide a unique opportunity to mitigate current plastic pollution. For instance, lignocellulose, primary polymeric structure found in plant cell walls, serves as an abundant and affordable raw material. More specifically, a number of polysaccharides including cellulose, starch, pectin, chitin, chitosan, and alginate provides exciting opportunity to replace conventional plastics. The utilization of these materials benefits from not only the high availability of raw materials, but also their supreme functionalities and excellent biodegradability.

Numerous research efforts have focused on biomass-derived materials—what would be the most desirable research direction? Maintaining the balance between sustainability and functionality of the products should be prioritized. Namely, the overall fabrication procedure and the end-of-life fate of products must adhere to the Green Chemistry Principles,[7,8] while the products also demonstrate excellent performance to the desired application field. The most popular research directions are classified as below:

(i) Utilization of biomass as a filler in polymer matrix.
(ii) Extraction of specific components, *e.g.,* polysaccharides, monomers, and chemicals.
(iii) *In-situ* fabrication of end products from biomass.

Early strategies often incorporated biomass into other polymers as filler through minimal pretreatments. The main objective is to obtain synergistic effects in mechanical properties by achieving homogeneous dispersion of the fillers in the matrix.[9] However, this approach can fail to fully utilize the potential of waste biomass. Firstly, the filler content in composites is limited to some extent, since the higher content can lead to agglomeration and eventually diminish the overall performance of the products. Secondly, mere utilization of biomass as filler without sufficient pretreatment can underutilize functional biomass constituents.

To overcome these drawbacks, the extraction of specific components—particularly polymers or monomers—has gained traction. It involves several procedures, mainly disruption of the recalcitrant lignocellulosic structure and separation, which depends on the type of starting material. Here, two routes are available for different purposes: extraction of polymers or further disintegration to obtain monomers.[10] The former includes the extraction of polysaccharides and lignin. It is an appealing strategy for various resources such as wood, as they are mainly composed of natural polymers. Furthermore, the extraction of natural polymers requires moderate pretreatment without further breaking the polymer chains, which can be directly utilized for polymer materials. Indeed, further processing of the obtained materials to nanofibers or surface-modified products is also appealing.[11] On the other hand, biorefineries, a well-established practice which can produce valuable chemicals, monomers, and even polymers (*e.g.,* polyhydroxyalkanoates (PHAs)), provide excellent reservoir for the chemical sciences and industry.[12,13] These include numerous chemical and biological processes to obtain high-quality chemicals that meet the demands of diverse fields. Specifically, monomers from biorefinery can be utilized in conventional polymer production processes with ease.

As a more specific strategy, *in-situ* fabrication of end products is feasible which includes few separation and purification steps. It aims to dissolve biomass and regenerate the lignocellulose structure in a desired supramolecular structure, producing lignocellulose films or engineered wood products.[14,15] To achieve this, several green approaches such as utilization of green solvents (*e.g.,* deep eutectic solvents), or physical techniques (*e.g.,* ultrasonication and microwave irradiation) can be employed. It is appealing that the properties of final products can be benefited from the lignocellulose or other natural-inspired functional structures.

Despite their promise, biomass valorisation technologies face challenges: (i) a complicated structure of biomass restricts a comprehensive understanding of the biomass composition and reaction mechanism; (ii) achieving both functionality and sustainability of the products may be contradictory. Nonetheless, these offer many exciting research opportunities regarding the novel feedstock selection, process optimization, characterization, and application. These solutions can offer renewable and biodegradable polymer products, accelerating the realization of a circular economy.

Recycling and upcycling of non-degradable plastic waste

While replacing conventional plastics with biodegradable alternatives is a long-term goal, the management of existing plastic waste is equally critical. Current plastic waste management heavily depends on landfill and incineration which generate greenhouse gases, and a considerable amount of waste is mismanaged.[1] Numerous plastic recycling and upcycling strategies have been developed towards more sustainable valorisation, while several solutions are already implemented in practical fields.

Recycling of plastics embraces physical and chemical methods to produce new plastics. A popular method among them is mechanical recycling, which involves separation, cleaning, and shaping processes with minimal chemical changes. Beyond manual sorting, optical sensors are recently used to classify a specific type of polymer from one another—which has been a major constraint to mechanical recycling. A combination of optical sensor techniques and machine learning can provide more efficient solution.[16] However, not all plastics are mechanically recyclable, often resulting in downgraded products. Furthermore, mixed plastic waste stream as well as impurities such as food, adhesives, inks, and other additives can significantly reduce the efficiency.

Chemical recycling can handle various drawbacks of mechanical recycling. Researchers have been investigated various interesting depolymerization mechanisms through solvolysis, photolysis, as well as electro- and mechanochemical methods.[17] These processes can yield monomers to produce new high-purity polymers, overcoming several disadvantages of mechanical recycling.

Common chemical recycling methods utilize acids, alcohols, as well as various chemical and biocatalysts.[18] Depending on the bonds to be cleaved (C–C or C–X, where X is a heteroatom), metal salts, zeolites, glycerol, methanol, ionic liquids, and others are popular choices. Moreover, similar approaches have been designed for chemical upcycling processes, producing a wide variety of value-added chemicals. Its example ranges from carbonaceous materials to fuels and chemicals for specific demands.[19] It is worthwhile to note that polymers including heteroatoms, such as polyesters, are prone to be processed than polyolefins in most recycling and upcycling strategies.

In recent years, emerging technologies such as UV-induced photocatalysis and electrocatalysis have been developed.[20,21] Furthermore, mechanochemical methods including ball milling and ultrasonication are also gaining interest.[22] Unlike common approaches, the reaction conditions of these methods are diverse—some reactions do not require any solvent or catalyst; however, these also involve chemical reactions. These attempts become more advantageous when the polymer is designed to be degradable in specific conditions.[23]

In conclusion, both mechanical and chemical recycling provide exciting opportunities to valorise plastic waste. Looking ahead, future research should focus on developing less energy-intensive and more universally applicable recycling and upcycling methods capable of handling heterogeneous waste streams. Further economic and environmental assessments can provide criteria for industrial feasibility of these processes.[24]

Perspective

These two approaches, valorisation of biomass and plastic wastes, should be simultaneously pursued to effectively mitigate the plastic pollution. The complexity of this global issue demands more innovative, interdisciplinary solutions. The ultimate solution cannot be achieved by scientists alone—active cooperation of entrepreneurs, policymakers, and the public is also crucial.[25, 26] In particular, the role of governments is of primary importance: they can collect informative data, enact regulations, and also promote new technologies and startups.[27]

As scientists who devote to alleviate plastic pollution, one should keep in mind that the ensuring green chemical sciences in entire life cycle of materials is essential—from pretreatment of raw materials to application of developed materials, as well as their sensible end-of-life scenarios. Green Chemistry and Green Engineering Principles can pave the way for achieving such goals, which serve as guidelines to minimize the environmental impact of the entire process.[28] Cross-disciplinary collaborations with experts can also create new opportunities. I firmly believe that it is our generation of Young Scientists—those most affected by the ongoing environmental crisis—who will rise to the challenge. I would like to eagerly participate in solving these problems throughout my academic journey.

Statement on use of AI

No AI was used in the preparation of this essay.

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Finalist

Waste is just a resource in the wrong place: the chemical sciences approach to transforming waste into valuable products

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While waste management may not currently be at the forefront of global conversations about sustainability and climate change, it remains a significant challenge that deserves more attention. Addressing environmental problems like pollution, biodiversity loss, and climate change requires a focus on waste and coordinated efforts at both the global and local levels. Rapid urbanisation, industrial growth, and rising consumer demand have led to a considerable increase in the amount and variety of waste,[1] creating a major global issue. According to the World Bank Group, global waste production is expected to reach 3.4 billion tons annually by 2050, up from the current 2.01 billion tons.[2] This will cause the environmental damage created by waste disposal to intensify, leading to higher levels of harmful emissions and pollution.

A promising approach to tackling this issue is the concept of "waste to wealth", which focuses on transforming waste materials into valuable resources or products.[3] This concept is a key principle of the circular economy, which aims to minimise waste, optimise resource utilisation, and promote sustainability.[4,5] It reduces environmental harm[6] while creating economic benefits. In this model, waste generated across various sectors can be recycled, repurposed, or converted into energy, materials, or other valuable products.[5] This approach not only conserves natural resources but also drives innovation, creates jobs, and stimulates economic growth. The United Nations Environment Programme (UNEP) reports that adopting waste prevention and management strategies could reduce global waste-related costs to $270.2 billion annually by 2050, and moving toward a circular economy could eliminate these costs and generate a net gain of $108.5 billion each year.[5] This shows the significant economic potential of a more sustainable waste management system.

Waste is an inevitable byproduct of human activity,[7,8] produced by individuals, organisations, and industries in different forms (liquid, solid, semi-solid, and gaseous), and comprises a wide range of materials.[9] Municipal waste, generated by households, businesses, and institutions, encompasses a wide range of materials, including organic waste such as food scraps, as well as packaging materials like cardboard, plastic wrap, and metal cans.[9,10] Managing these types of waste requires sorting, recycling, and reducing their impact on the environment. Industrial waste generated from manufacturing, construction, and similar activities is often complex and hazardous, containing toxic chemicals, solvents, heavy metals, and other pollutants that pose a significant risk to soil, water, and air quality.[11] Agricultural and animal waste, like crop residues, manure, and food processing byproducts[10] can also cause environmental problems if not correctly handled. However, with the right strategies, these waste products can be converted into valuable resources.

Promoting sustainable waste management is a key responsibility of governments and regulatory bodies, which can be achieved by establishing policies and guidelines that support eco-friendly practices. One example of such a policy is Extended Producer Responsibility (EPR), which holds companies accountable for the entire lifecycle of their products, encouraging them to design and manufacture more sustainable and recyclable goods.[11] Governments can also help by establishing standards for waste disposal, recycling, and treatment to reduce pollution, protect public health and promote innovation in waste management. By offering structure and support, they can foster an environment that promotes sustainable waste practices, ultimately benefiting both society and the environment.

In complementing government efforts and initiatives, researchers in the chemical sciences are advancing methods for processing and valorising waste. These innovations include the transformation of waste into high-value materials, helping to reduce landfill accumulation while offering environmentally friendly alternatives to conventional manufacturing processes. Advanced chemical processes can help manage, process and upgrade municipal waste. For example, chemical recycling techniques break down materials such as paper and plastics, enabling them to be reused in new products. UBQ Materials, an Israeli cleantech firm, has developed new processes that convert unsorted household waste, including organic matter and hard-to-recycle materials, into a cost-effective composite material.[12] This material contributes to the reduction of greenhouse gas emissions, decreases dependence on conventional plastics and lessens the demand for the extraction of natural resources.

Plastics can be processed through methods such as pyrolysis, which converts them into oils, aromatics, and olefins for use as fuels or raw materials.[13] In Mexico, Petgas is addressing plastic pollution by utilising pyrolysis to convert waste plastics into fuels such as diesel, gasoline, and kerosene, producing hundreds of gallons of fuel each week.[14] Waste-to-energy technologies, such as incineration and gasification, convert waste into electricity or heat. For example, InEnTec employs plasma gasification to break down hazardous and biological waste into synthesis gas, which can be further processed into clean fuels and chemical feedstocks.[15] Additionally, anaerobic digestion uses bacteria to break down organic waste, generating biogas for clean energy.[16] Organic waste, sewage sludge and other byproducts of municipal waste can also be transformed through composting to make nutrient-rich fertilizers for agriculture.[17] On a larger scale, Johnson Matthey, a company with extensive expertise in Platinum Group Metals (PGM) chemistry, catalysis and process technology, is developing sustainable fuel technologies by converting various waste materials into hydrogen, methanol, and ammonia.[18]

Industrial waste can be managed effectively using methods such as hydrometallurgical processes, including leaching, purification, and electrowinning, as well as pyrometallurgical methods, including smelting and refining.[19] These methods provide effective solutions for managing industrial waste. Gold, copper, zinc and other heavy metals can be recovered from hazardous waste streams, electronic waste and industrial effluents, enabling their reuse across various industries. By employing a hydrogen-based process, HyProMag, a company based in Birmingham, UK, specialises in extracting rare earth magnets from discarded hard disk drives.[20] This is done by efficiently separating magnet materials from electronic waste, addressing the global need for rare minerals essential in low-carbon technologies. Additionally, chemical reactions like catalytic oxidation or reduction break down hazardous substances into non-toxic products. For example, volatile organic compounds (VOCs) can be oxidised into carbon dioxide (CO_2), which can then be converted into valuable chemicals, such as methanol,[21] a promising transportation fuel, and formic acid,[22] which can be used in fuel cells. Carbon Recycling International is the leading company in CO_2-to-methanol technology, the only company to date to have successfully implemented commercial-scale plants dedicated to converting CO_2 into methanol, with an installed capacity exceeding 200,000 tonnes of sustainable methanol per year.[23]

Agricultural waste also presents sustainable and cost-effective opportunities for valorisation through various methods such as composting, fertilizer production, and renewable energy production.[24,25] In line with the green chemistry principle of utilising renewable feedstocks, agricultural waste can be converted into valuable products through biomass conversion and processing techniques. For example, waste vegetable oils or cooking oils can be converted into biodiesel through a chemical process called transesterification.[26] Biodiesel, compared to petroleum-based diesel, is an environmentally friendly fuel and has lower emissions. Lignocellulosic or non-edible biomass has been used in various applications, including energy production through combustion, animal feed, textiles in the form of cellulose-based fibres, paper, and pulp, as well as the production of other materials, such as sugars, which are further utilised in different applications.[27] Crop residues can be processed through enzymatic or chemical hydrolysis to break down cellulose and hemicellulose into fermentable sugars, which can then undergo fermentation to produce bioethanol- a renewable energy source used as a fuel for vehicles.[28,29] Through its advanced biorefinery technologies, DuPont transforms agricultural residues, such as corn cobs and stalks, into valuable products like cellulosic ethanol and other bio-based materials, which serve as essential building blocks for the production of fuel additives, solvents and biodegradable polymers.[30] This highlights the potential of waste-to-wealth innovations within sustainable chemistry. Some universities have also established spin-out companies that contribute to waste valorisation. Lixea, from Imperial College, London, converts waste wood into renewable chemicals,[31] while Keracol, from the University of Leeds, develops plant-based cosmetic ingredients.[32] These processes demonstrate how green innovations in the chemical sciences can drive both commercial and environmental benefits.

To fully realise waste-to-wealth initiatives, industries will need to adopt sustainable practices, governments will need to enforce robust regulations and research to develop innovative technologies will need to continue. The chemical sciences are central to sustainable waste management and valorisation, enabling the transformation of waste into valuable products that promote a circular economy and minimise environmental impact. Through processes such as those outlined above, diverse forms of waste can be transformed into high-value products and commodities. These innovations not only address the challenges associated with waste disposal but also open opportunities for resource recovery and energy generation. While some companies have demonstrated the potential of waste valorisation through chemistry, scaling these solutions globally requires greater investment, collaboration, and policy support. By building on existing progress, waste can be transformed into a valuable resource. The chemical sciences are inevitably promoting a circular economy where waste becomes an asset rather than a burden, paving the way for a more sustainable and resource-efficient future.

The statement on use of AI

Grammarly and ChatGPT were used to enhance the language, clarity and readability of this essay. AI tools were not involved in drawing scientific conclusions or generating references.

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Under-18 Finalist

Sustainable and environmentally-friendly strategies for dry battery recycling and utilization in the chemical industry

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Dry batteries play an important role in our daily lives, such as remotes, some electric toys, watches, etc. More than 1.9 million tons of waste dry batteries are produced worldwide every year, but less than 50% of them are recycled.[1] The primary materials in dry batteries include zinc, manganese, copper, cobalt, nickel, lead, etc., most of which are heavy metals. If not properly handled, these substances will penetrate the soil and water source system, causing serious damage to the ecosystem and threatening the health of humans and wildlife.[2]

Cobalt often exists in the form of hydrated cobalt oxide and cobalt carbonates in natural water, where it may precipitate on the bottom of the water, or be adsorbed by the bottom material. When the concentration of cobalt in the soil is 10mg/L, crops can be killed.[3] When the concentration of cobalt in the human body is too high, it will stimulate the increase of serum alpha globulin and polycythemia, and the destruction of pancreatic alpha cells can temporarily increase blood glucose.[4] Manganese is another example. Although Manganese is an essential part of the biological daily life activities, excessive emissions result in serious influence on the environment. When it is present in excessive amounts, it becomes toxic to plant cells.[5] Not only affects growth rates, but also the chlorosis in leaves (interveinal and marginal) and necrotic leaf spots.[5] In addition, the impropriate processing of dry batteries brings certain safety risks. Such as the explosion resulting from the residual reactive chemical composition.[6] On the other hand, the recycling of dry batteries can effectively alleviate the shortage of metal resources, the metal in dry batteries (Pb, Mn, Zn, etc.) plays a vital role in daily industrial production. Therefore, it is particularly necessary to solve the problem of battery waste through innovative recycling technology and sustainable practical measures. This essay will discuss the challenges that we face and the current method also the future development of processing dry batteries, to protect our planet and promote sustainable development.

Recovering nanomaterials from battery and electronic waste is a great idea.[7] The recycling of nanomaterials offers a variety of benefits, including recovering heavy metals (zinc, manganese, etc.), treating harmful gases (SO_2 and nitrogen oxides) and protecting the environment. The efficient adsorption and catalytic properties of nanomaterials (such as gold and iron oxide nanoparticles) can be further used for environmental remediation (wastewater treatment, air purification) and resource recovery, alleviating the scarcity of strategic resources such as cobalt, lithium, rare earth, etc.

Our current recycling method involves dissolving the metal components in the dry cell by soaking them in concentrated sulfuric acid, followed by the synthesis of nanomaterials (such as ZnO, MnO_2 and graphene composites) through precipitation and extraction. In practical applications, the purity of ZnO from zinc manganese batteries is as high as 98%. The recovery rate of zinc and manganese by hydrometallurgical process is more than 99% and 95%, respectively.[8] However, there are still some issues in this process. The particle size and surface activity affect Biosafety (for example, carbon nanotubes may cause pulmonary fibrosis), and a standardized risk assessment framework needs to be established. Furthermore, Hydrometallurgy produces acidic wastewater, and pyrotechnics releases volatile organic compounds, which need to be purified in combination with other technologies. The high costs of this process need government support to ensure its sustainability.

The collaborative utilization of waste dry batteries and biological waste is another promising method.[9] A single chamber mediator free microbial fuel cell (db-mfc) was constructed by using the zinc shell of the abandoned D-type zinc carbon battery as the anode, a carbon rod as the cathode, and kitchen sludge treated with nitric acid as the substrate. A modularised MFC with a total volume of 1000 L, operated successfully over 12 months.[10] Four units in the series can illuminate an LED for several weeks to show the possibility of practical application. Meanwhile, the scheme is low cost and has simple processes, which is suitable for large-scale promotion in developing countries. This method is still in the experimental stages and requires development before commercialization.

Manganese is the main material of dry batteries. So, the recycling of manganese will largely determine the recovery efficiency of dry batteries. Currently, we are lacking the feasible technology of recycling Mn. In the acid-leaching process, when only sulfuric acid is used as a solvent, the leaching rate of manganese is only 30%. However, when sulfuric acid is mixed with hydrogen peroxide, the leaching rate of manganese reaches 100%. After ozonation, 95.8% of manganese dioxide was successfully recovered, and the manganese content reached 55.5%. The ozone utilization rate was 95.8%, and the reaction rate was also improved.[11] Afterwards, the recovered MnO_2 will be reduced to metallic manganese by aluminothermic reaction in the electric furnace. However, the high price of the equipment reduces the potential of this approach to some extent.

The use of organic acids is also a notable alternative. Recent studies have shown that organic acids (such as citric acid, oxalic acid and acetic acid) have significant advantages in the application of metal leaching from waste dry batteries. Compared with traditional strong acids (such as sulfuric acid or hydrochloric acids), under the same conditions, organic acids not only improve the leaching rate, but also reduce secondary pollution. Yamaguchi et al. (2017) reported that the leaching rate of manganese by citric acid was more than 90%.[11] Furthermore, organic acids have good biodegradability, which can significantly reduce environmental pollution in the leaching process.

The recovery of dry batteries by chemical methods has great benefits for human society. From the perspective of the environment, recovered metals effectively reduce human dependence on primary mineral resources and reduce carbon emissions. From an economic point of view, improving the metal recovery rate reduces the recovery cost, promotes the development of innovative industries. From a social perspective, innovation not only improves people's awareness of environmental protection, promotes the improvement of relevant policies, but also improves resource security and the country's ability to ensure resources.

Currently, different methods of recycling dry batteries are facing challenges. For instance, the recovery process of high-purity metals (such as manganese) is complex, especially difficult to meet the demand of high-end applications such as high-strength steel.[11] Although existing technologies perform well in small-scale experiments, they still face problems such as reduced efficiency and increased costs in large-scale industrial production. Additionally, the metals in dry batteries' price are fluctuating, so the income is unstable, the process is hard to continue during large-scale recycling. The development of these methods in the future needs the support of the government and relevant institutions to promote relevant chemical research by improving the relevant policies, reducing the energy consumption and complexity of the methods, and improving the popularization ability.

Statement on use of AI

No AI technology was used to prepare the essay.

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Finalist

Chemical sciences: changing how plastics are recycled; a review of current research and innovation

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The global issue of plastic pollution is the most significant environmental challenge we face today. With global reaching implications plastic waste, both macro- and micro-, impacts human and animal health, pollutes inorganic aspects of our environment, in particular our oceans and waterways, and uses vast amounts of energy and resources. In 2021, Plastics Europe published that 390.7 million tons of plastic were produced across the world, with only 14% of plastic packaging collected for recycling.[1] A staggering 40% of all plastic goes to landfill.[2] Ecologists estimate that over 150 million tonnes of plastic waste is in our oceans and they predict that by the end of 2050, our oceans will contain more plastic, by weight, than fish.[2] If left unchanged, this issue will worsen as the global population is expected to increase to 10 billion in the next 35 years.[3] This problem will continue to impact every living creature on the planet.

Industry and science are working together to mitigate the impact of plastics on the environment, human health and the global economy. The race for innovative solutions in how we produce, use and recycle plastic materials has begun. A shift towards a circular economy - where plastics are reused, recycled, and continuously reintroduced into production cycles - is essential if we hope to find solutions to the growing challenges associated with plastic waste. As highlighted in The New Plastics Economy, a sustainable circular model focuses on maintaining the value of plastics in the economy, reducing environmental harm and encouraging ecologically sound practices.[2] This model suggests 20% of plastic packaging, by market weight, is already reused, as people actively refill bottles and reuse bags, wrapping or rigid packaging.[2] Another 30% of plastic waste requires redesign.[2] These products are of the small-format variety or ones with multi-material packaging, both being difficult to recycle due to size or the inability to separate the different types of materials.[2] In these instances, there has been consumer pressure on manufacturers to use materials other than plastic to contain products. This has seen a shift to the use of paper for food containers, dispensing medicine, drinking straws and shopping bags. The circular economy vision is central to global initiatives, including the United Nations' draft global plastic treaty, and its call for international cooperation to curb plastic pollution.[4] In addition, the Centre of International Environmental Law, emphasises that the circular economy must consider the full plastic life cycle, from extraction through to disposal and all its impacts, not just waste management. It must acknowledge the need to uphold human rights, international agreements, policies and safe design.[5] However, the plight of the remaining 50% of plastic waste is still a concern. Although incentives, policies and social campaigns may encourage people to recycle plastic waste, many of the current recycling systems are inefficient, costly and just as harmful to life as the pollution itself.

This is where chemistry enters the realm of the circular economy. In devising innovative, safe and above all high-yield, scaled-up methods of recycling, global chemists are setting the scene for improved environmental outcomes. One of the most widely used and cost-effective methods for recycling plastics is mechanical recycling.[6] Plastic containers or packaging is chopped into smaller pieces by a bladed machine, melted down and reformed into another product. While mechanical recycling is relatively simple, the raw material - plastic chips, for example - degrades over time, limiting their reuse in any high-quality product. Therefore, there is a need for more advanced applications, such as chemical recycling. Simply put, the chemical method for recycling plastic involves breaking the bonds between the long polymer chains, transforming them into smaller molecules that can be used to create new, higher-quality plastics.[6] With the circular economy in mind, this needs to be done in the most economically efficient, least environmentally harmful way. A notable discovery in this method has been the development of photocatalysts, which use solar or light energy to drive chemical reactions that in turn break down the plastic waste. Researchers from Swansea University have been experimenting with the reforming of lignocellulose into hydrogen using a CdS-CdOx photocatalyst with sunlight to power the process.[7] This method reduces both the amount of energy normally consumed by recycling as well as the ecological impact as it can be carried out within a closed environment and produces hydrogen gas, a naturally occurring substance and possible alternative energy source. This is a win-win situation when adhering to the circular economy model.

However, although successful in its recycling aim, this method needs to be upscaled to cope with the volume of plastic waste.

Another key approach in chemically reprocessing plastics into reusable materials is pyrolysis. This involves using thermal degradation, heating the plastic molecules, to break them down into smaller molecules using a catalyst to improve the efficiency of the process. The catalyst lowers the activation energy needed to start the breakdown. A study published in *Nature* demonstrated the breaking down of polyethylene into monomers with a recovery rate of over 96%.[8] Again, this demonstrates how chemical processes can improve the circular economy of plastic recycling. However, there are barriers associated with using catalysts, particularly in terms of their economic feasibility, chemical stability and ecological impact.

Similarly, research into catalytic conversion, such as platinum-supported catalysts on γ-alumina, shows how polyethylene can be converted into recycled products.[9] This method not only produces high yields, upwards to 80%, but also has less environmental impact over other methods, produces minimal waste and occurs without using a solvent. Chemical recycling methods, particularly those involving catalysts and pyrolysis, give good yields, however there is still work to be done on the environmental impact and upscaling of these methods.[10]

Experimentation into the use of natural catalysts, such as enzymes or plant-derived substances, are showing that plastics can be recycled in an environmentally responsible way. Chemists in France have explored enzyme-based methods for depolymerising plastics, such as polyethylene terephthalate (PET), using PET hydrolases.[11] Their initial findings show over 90% depolymerisation efficiency is achieved in a matter of hours, adding to the sustainability and large-scale use of this method when recycling plastic. Researchers in Malaysia highlighted that some bacterial enzymes have similar structures to PET hydrolases and could potentially be used for the biocatalytic recycling of PET.[12] This method is currently used in several countries, including Japan, as a new sustainable way to produce environmentally sustainable recycled plastics.[11]

Researchers at Washington State University have made significant advances in the use of plant-extract chemicals in breaking down plastic waste.[13] This team developed a process which breaks down plastic resin using a catalyst and renewable phenylpropene derived from plants like nutmeg and cinnamon. This was achieved at a relatively low temperature and shows the potential of this method as a more sustainable alternative to high energy driven systems. Research has also explored the use of lignin, a by-product from plant-based materials, as a renewable product used in chemical recycling of plastics.[13]

Some chemists are taking an entirely different approach and focusing their research on creating more eco-friendly alternatives to epoxy resins and fossil-fuel based plastics. Researchers at the University of Houston have developed recyclable thermosets by replacing bisphenol A with renewable chemicals derived from soybean oil and salicylic acid.[14] These plant-based derivatives create materials that are both durable and recyclable. Scientists at the University of Connecticut have focused on creating plastic-like materials from proteins.[15] In doing so, they have been able to develop a large 3D structure in which the polymer acts like plastic and it can easily biodegrade due to enzymes breaking the amide bonds. Researchers have also targeted the recycling of scrap pieces of clothing.[15] It was reported in 2024 that 92 million tonnes of textile waste was produced worldwide.[16] By using textiles destined for incineration or landfill, natural fibres are re-spun into yarn and are rewoven into fabric and polyester textiles are shredded into chips and manufactured into new polyester fabrics.[16] This demonstrates a sustainable and circular economy, allowing for more efficient recycling, and a higher recovery of the starting material.

In conclusion, the research reviewed in this essay highlights the clever chemistry being developed to confront the growing problem of plastic waste. Innovative teams are using conventional chemical methods to improve the recycled product yields and reduce environmental impacts, exploring the use of natural catalysts and rethinking the chemical composition of plastics altogether. Global legislation and agreements, including Conference of the Parties (COP) mandates and the UN Sustainability Goals, highlight the critical role in adopting a circular economy approach to combat the global plastic pollution crisis. The chemistry contribution to this is seated in the development of processes that can be upscaled, are cost-effective and environmentally responsible. However, the responsibility for addressing plastic waste lies with all of us - consumers, policymakers and industries - not just chemists.

Statement on use of AI

No AI was used in the preparation of this essay.

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Finalist

Sustainable production and consumption: the future of polymers and plastics in society

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In a world where staggering inflation has led to astronomical price rises and Governments stepping in to avoid financial crises, the chemical sciences play a vital role in the conversion of what should be considered valuable by-products, once discarded by a wasteful society, into useful products.

Plastic products have in recent years become the villain of the single-use society. While it is undeniable that the rate at which fossil fuels are consumed and plastics discarded is untenable for the planet from both an economic and environmental sustainability perspective, we should not turn our backs on polymers but instead should focus on a shift to renewable resources and circularity, ideally with an aim to upcycle, in order to increase the wealth of the planet monetarily and in its natural abundance.

Herein, I will focus on addressing how the chemical sciences can transform the beginning and end of a polymer's journey through society as a nod to the United Nations' Sustainable Development Goal (SDG) of Responsible Production and Consumption (SDG 12).[1]

From by-products to new products

Whilst it can be said that value has been added to waste otherwise destined for landfill through the generation of power *via* energy recovery, this is not without its problems. For example, it has been reported that burning waste produces equivalent emissions as burning coal per unit of energy produced.[2] Furthermore, this only serves what should be considered an archaic linear economy, rather than adding long-term value to the circular economy.

Instead, better use needs to be made of waste by-products, by turning them into value-added products. For example, the processing of citrus fruit skin, otherwise considered waste from the food industry, elicits a ready supply of limonene, the compound associated with the fragrance of lemons, that can also be turned into a monomer which in turn can be used to form biobased polyesters,[3] a form of polymer that can be readily chemically recycled. This is just one example of food waste being turned into biopolymers, with many more discussed in the review by Srivastava *et al.*.[4] More recently, the same Nottingham-based research groups published on the ability to use pinene to synthesise monomers more commonly associated with petrochemical feedstocks.[5] In fact, in current journals such as *Sustainability* and *Polymer Chemistry*, amongst others, it is easy to find a multitude of articles on related research, with more being published on an almost daily basis.

Another example of the use of a by-product made possible by the chemical sciences is Carbon Capture, Utilisation and Storage (CCUS). This has two-fold benefits of not only reducing the carbon released into the atmosphere but also creates a potential additional revenue stream for those that invest in the technology.

Not only can polymeric materials play a vital role as ad/ab-sorbents in this developing technology,[6] with waste plastics being suggested as useful for CO_2 capture,[7] the CO_2 can itself be used to produce biobased polymers.[8,9] For example, polyols have been produced industrially for over a decade using CO_2 as the starting material.[10] Furthermore, this also removes the need for highly toxic phosgene from the syntheses of polycarbonates and polyurethanes.[11]

Recyclate

Whilst recycling can be subdivided into both mechanical and chemical, it is the latter where the chemical sciences can be seen to be of most obvious use, however, that does not mean that the chemical sciences are not at the centre of improvements being developed for mechanical recycling, and the resulting recycled materials.

In short, mechanical recycling is not a process that directly requires the chemical sciences as it is a physical process of grinding and reforming (e.g. through extrusion), the problem with this is the inability to remove any contaminants from within the material, things which were initially intentionally included such as antioxidant additives and inks. Through repeated recycling, the concentration of these will increase, potentially disrupting the properties of the resulting product. This has also led to recyclate being restricted so that it does not come into direct contact with food and often means that products are rarely made from 100% recycled plastic in order to mitigate some of these changes. This also means that material recycled by this method cannot be recycled indefinitely, however, new science has aimed to tackle some of these issues. For example, innovative additives have been developed that allow manufacturers to track the number of cycles that a batch of material has been through as a way to ensure quality.[12] Though this may sound counterintuitive given that we have just discussed the limitations of mechanical recycling associated with contamination, this can minimize the need for the incorporation of virgin material / waste of material that is still perfectly suitable for its intended application, ultimately increasing the value of recycled material as it now comes with something of an in-built guarantee. To this end, some of these emerging technologies are making the transition out of the academic research lab into industry, mostly via the means of spin-out companies. For example, the Polarfin® products produced by Interface Polymers which have been invented with compatibilization and circularity in mind.[13]

Within chemical recycling, further subdivisions into gasification, pyrolysis and depolymerization can be made. It is the latter that I will focus on here.

At the time of writing, there had been nearly 18 000 publications containing the word depolymerization in the last 100 years. Of those, nearly 6% occurred in 2024, while nearly 300 came from the first 2 months of 2025![14] The technology is not new, alternative methodologies and an expansion of the materials to which depolymerization can be applied has exponentially increased in the research labs and therefore scientific literature in recent years yet, industrially, this is lagging behind. The chemistries available for this are thoroughly reviewed by Clark & Shaver,[15] for several common polymer types. More importantly, the literature discussion has also turned to the design of polymers specifically with this end-of-life fate in mind.

Additionally, a recent review highlighted the value that can be added when recycling the plastic most commonly used in single-use applications, polyethylene terephthalate (PET).[16] Herein, the authors suggest that PET, reportedly worth 0.22 $/kg at the time, can be upcycled into a range of materials worth anything from double the price (0.48 $/kg for ethylene glycol) to 45 times the price if used in the creation of carbon nanotubes.

Furthermore, in recent years there have been increasing reports of upcycling polycarbonates. Bisphenol A (BPA), a now regulated known endocrine disrupter, is one of the by-products of the hydrolytic breakdown of poly(bisphenol A carbonate), making it of high importance to recycle waste polycarbonate, so as to prevent the environmental release of BPA. Some of the upcycled applications include as epoxy curing agents,[17] polyurethanes[18] and solid-state batteries.[19] The latter being of further importance as the ability to develop new battery materials is a further demonstration of the chemical sciences increasing the global wealth on a sustainable level.[20] Not least because the use of transitions metals (e.g., lithium in traditional Li-ion batteries) comes with a heavy caveat at the human level, where workers in less-developed countries are exploited in mines, but these elements are also a finite resource[21] alongside the increasing demand for energy storage solutions as renewable resources increase and options such as electric vehicles become more prevalent.

Whilst depolymerization seems to be the chemistry answer to the globe's plastic problems, the choice of which process(es) to adopt should be made with the principles of green chemistry in mind.[22] Currently, mechanical recycling is considered the greenest form of recycling as no further chemicals/solvents are required. This makes an assumption that the energy used is renewably sourced.

Ultimately, the cost of recycled material SHOULD be cheaper than the virgin equivalent, given the costs associated with sourcing and processing raw materials / fossil fuels. However, currently, this is not the case. Figures reported at the beginning of 2024 suggest that although the price of both virgin and recycled polymers have decreased, this has not occurred at the same rate, increasing the gap between the two.[23] Whilst there is a global oversupply of petrochemical-derived starting materials such as ethylene, this is unlikely to change unless more is done at a (inter)national regulatory level.

All the chemical science advancements in the world will be irrelevant if recycling is not simplified and incentivized so that rates are dramatically increased, not just for plastics but all materials. Current recycling rates can be difficult to determine, with many different figures reported.[24,25] This in part is not helped by the seeming lack of transparency surrounding the fate of materials put into a 'recycling bin'.[26] What can be agreed on, regardless of the accuracy of reported figures, is that the answer is simply not high enough. There can be all the advances in the chemical sciences discussed here and many more, but without commitment on the global scale at the biggest political level to enact change, the wealth of the planet will not improve.

Statement on use of AI

Use of Artificial Intelligence (AI): No AI was used in the preparation of this essay.

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Finalist

Waste not want not – how chemical sciences can transform lignin waste into high valued products

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Each year, one billion tons of petrochemical based products are produced for application in electronics, medical equipment, transport and packaging.[1,2] It is therefore not surprising that a large portion of the direct CO_2 emissions relating to global warming come from the petrochemical industry.[1] To address this, the United Nations have introduced sustainable development goals which instruct local governments and businesses to invest in renewable energy sources.[3] This has prompted industries such as textiles, food and construction to turn towards the production of bioderived energy and materials.[4] The sustainable nature of emerging bioderived materials, and their role in the circular economy is clear. However, industrial waste materials that have the potential to be transformed into valuable products are being neglected.

In the pulp and paper industry, over 50 million tons of a waste product named lignin is produced each year.[5] Lignin is a cheap, renewable polymer found in plant cell walls.[6] It is also the second most abundant renewable energy feedstock and the only large source of renewable aromatics.[5] All of which give it immense potential to be used as a petrochemical alternative. However, only a small fraction of lignin is used in this way. The rest is burned as a low-cost fuel, which contributes to global warming.[5]

This essay aims to address current challenges in the utilisation of lignin and provide an insight into how chemical sciences can turn this waste material into valuable products. In doing so, I will first address challenges that chemical sciences cannot control. After, consideration will be given to the current approaches that chemical sciences are taking to valorise lignin by using methods they can control. For each approach, possible improvements will be considered.

Uncontrolled Factors

To be commercially successful, products must be consistent in design and function. For reproducibility within products, manufacturers rely on starting materials with known chemical structures and established chemical properties. Manufacturers also look to rely on resources that are cheap and abundant. While lignin is cheap and abundant, establishing consistencies in its chemical behaviour is often challenging due to lignin having an unpredictable structure and varied molecular weight.[7] The variation in structure and molecular weight are influenced by factors such as: plant type, plant age, growth environment and the process chosen to isolate lignin from its source.[8, 9]

Despite there being recognition of each factor being influential, there is limited literature available that describes the extent of the effect that each has on the chemistry of lignin. This may be due to a lack of control of the materials made available by forestry commissioners, resulting in these factors not being fully explored. Restricted access to certain wood types can result in challenges when pinpointing unique structural features that may be linked to different plant types or certain growth environments. In turn, this can limit the understanding of how differences in these structural features may influence the reactivity and valorisation potential of lignin.

In addition to limited control of resources, the chemical sciences are also restricted when it comes to the information available regarding the plant source and growth environment of commercially purchased lignin. This makes chemical properties such as the solubility and degradation temperature of lignin samples difficult to predict between batches, even when they are sourced from the same supplier. Hence, researchers can be confronted with challenges regarding reproducibility of experimental results.

The difference in behaviour between each batch purchased from the same source is likely linked to unwanted structural modifications that occur during the lignin extraction process.[10] These modifications can be difficult to control, and likely correspond to the high temperatures and harsh chemicals used during isolation.[11] For example, the pulp and paper industry use a series of chemical treatments to separate lignin from the cellulose and hemicellulose that make up wood chips.[11] This results in partial breakdown of the lignin chain and increases the variability in structure, and behaviour, between batches.

However, all is not lost. Recognising and addressing these solvable challenges will provide opportunities for the chemical sciences to find a new approach in their research. By working towards an understanding of the influence each factor has on the overall structure and reactivity of lignin, better insights into approaching valorisation can be achieved. As a start, it is possible for industrial partners such as biorefineries and forestry commissioners to invest in collaboration with academia. By increasing communication between all parties, and opening access to various plant samples, the chemical sciences can use their findings to help advise and monitor the planting of new trees to harvest materials. This will aid in the full utilisation of this natural resource, and grow the forestry sector economically.

It is also possible for the chemical sciences to overcome valorisation challenges by considering possible improvements to the isolation process. For example, reducing the temperatures needed to isolate lignin from its source can reduce the potential breakdown of its chains. This can also reduce the energy consumed by biorefineries, in turn, decreasing their CO_2 emissions and aiding the progress of the sustainability goals set by the United Nations.

Controlled Factors

For now, the chemical sciences are approaching lignin valorisation by focusing on methods that can be controlled. By using the available literature which describes the biorefinery and extraction processes used to isolate lignin, it is possible to fully understand the potential consequences each step in the biorefinery and extraction processes can have on the structure and reactivity. This approach better allows researchers to consider which methods provide starting materials that are consistent in their chemistries.

Having consistent chemistry across multiple batches of lignin will allow researchers to find new ways of controlling specific chemical properties to tailor the material to be suitable for multiple applications. This is a crucial part of the valorisation of lignin. There is an abundance of literature available describing how scientists can do this by adding reactive substituents to the lignin chain for controlled modification.[12-14] The ability to carefully manipulate the reactivity of lignin through structural modifications can lead to consistent behaviour across different batches, ultimately making it more suited to commercial applications. If adequate modification can consistently be achieved, then lignin could be included in the production of materials such as foams, resins and biofuels.[15] This would allow it to be used in applications such as adhesives, coatings and insulation.[16] The wide range of products that lignin can become highlights the importance of this research and lignin's potential to be a reliable petrochemical alternative.

For profitable applications, it is important that modification can be achieved across lignins from different plant sources that have been extracted through various methods. To be able to do this, there needs to be enough spaces available along the lignin chain where reactive groups can be added. The availability of these groups will be influenced by the uncontrollable factors discussed previously. Therefore, it is extremely important that the discussed approaches are fully considered to broaden our general understanding of lignin and how it can be valorised.

If the chemical sciences can achieve a full understanding of the structure and properties of lignin, it is crucial that academia shares its knowledge with governing bodies to highlight the way this waste material can be used to reach the sustainability goals set by the United Nations.

Overall, the chemical sciences have an influential role to play in turning waste lignin into valuable products. The uncontrollable nature of the factors which influence the behaviour of lignin, and the limited resources available to the chemical sciences to overcome these challenges, are a barrier towards successful lignin valorisation. However, it is possible for the chemical sciences to change their approach. Opening communication between academia, industry and governing bodies can provide the opportunity for the chemical sciences to gain access to more materials which can be used to deepen their understanding of lignin. This understanding can be used to support plans to sustainably manage forests by advising and monitoring the planting of trees. The potential success in this approach is clear in current collaboration projects across the world. For example, Michigan State University have partnered with industry to identify how lignins from different sources can be used to replace petrochemical based epoxy resins.[17] In addition, the University of Glasgow are collaborating with industry to understand how co-products from the forestry sector can be turned into high-valued products through controlled modification.[18]

For progress to continue, it is essential that full responsibility is not left with the chemical sciences. Instead, it is important that the government and industry share the responsibility by continuing to invest in the valorisation of waste products such as lignin. In doing so, a shared understanding of lignin can be used to sustainably manage our forests and natural resources, while economically growing the forestry sector. Moreover, the dependence on petrochemicals for everyday products will be reduced. In turn this will decrease the direct CO_2 emissions which are related to the petrochemical industry, moving us towards a sustainable future.

Statement on use of AI

AI technologies were not used in the preparation of this essay.

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Finalist

Wonderland reimagined - how functional upcycling unlocks the door to value-added materials

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Reimagining what lies down the rabbit hole. If it were plastic waste, its foundations date back to the 1920s to 1950s.[1] During this period, numerous synthetic polymers, such as poly(methyl methacrylate) (PMMA) or poly(vinyl chloride) (PVC), were developed that remain key components of widely used plastics today.[1] Polymers are high molecular-weight molecules composed of multiple repeating low-molecular-mass units.[1] Food packaging illustrates the strengths of synthetic polymers, including their lightweight nature, resistance to moisture and ultraviolet (UV) light, and their ability to shield food from contamination and microbes, significantly extending shelf life.[2] However, the chemical nature of commercially successful polymers poses substantial challenges regarding the end-of-life management of plastic waste.[3] Globally, only 20% of plastic waste is recycled, 25% is incinerated for energy recovery, and over 50% is discarded in landfills.[3] As a result, the accumulation of plastic waste in ecosystems causes an environmental crisis of unprecedented scale.[3]

Within this essay, first, the interconnection between the plastic waste crisis and the Sustainable Development Goals (SDGs) will be explored,[4] followed by an examination of chemical strategies to transform plastic waste into value-added materials. Finally, the realistic implementation of these strategies will be evaluated, focusing on their societal and policy implications.

The plastic waste crisis and the Sustainable Development Goals (SDGs)

Offering a universal development framework that calls for collective responsibility from all nations, the 17 SDGs intend to eliminate poverty and promote prosperity, while safeguarding the planet.[4] For example, the third SDG, *"Ensure healthy lives and promote well-being for all at all ages",*[4] highlights the need to reduce the harmful effects of plastic waste. Throughout their whole life cycle, plastics may release potentially cancerogenic or endocrine-disruptive chemicals contaminating our ecosystems, food, and water.[5] Microplastics have been found in drinking water or human tissues, posing risks for respiratory and cardiovascular disease.[5] Indeed, retrieving discarded plastic waste from the environment and designing new plastics that do not release hazardous chemicals or microplastic could help alleviate these health risks.

Mitigating the plastic waste crisis could also contribute to the fifth SDG, "*Achieve gender equality and empower all women and girls*".[4] In many parts of the world, women disproportionately bear the burden of waste management through domestic responsibilities. In areas lacking formal waste management systems, improper waste disposal and open burning of plastic waste have a more significant impact on the health of women and children.[6] The tenth SDG, "*Reduce inequality within and among countries*"[4] also intersects with the plastic waste crisis. For instance, Turkey has become the primary destination for Europe's exported plastic waste in 2020 and 2021, receiving half of all plastic waste from the 27 European Union (EU) member states.[7] This example highlights the global inequality in waste management. Countries in the Global North, like the EU member states, should implement policies that ensure waste processing within their territories and prohibit illegal plastic waste exports to countries in the Global South.

Tackling the plastic waste crisis by removing plastic waste from marine ecosystems is also critical to attain the fourteenth SDG, "*Conserve and sustainably use the oceans, seas and marine resources*".[4] The accumulation of plastic waste in the oceans significantly accelerates biodiversity loss and ecosystem degradation.[8] Finally, the twelfth SDG, "*Ensure sustainable consumption and production patterns*"[4] aligns with the idea of transforming waste into a resource, transforming a linear plastic economy into a circular one.

Chemistry - a key to mitigate the plastic waste crisis

In "*Alice in Wonderland*", Alice finds herself in a hall of locked doors. To access the beautiful garden behind one tiny door, she must alter her size to fit through. If we imagine that behind these doors lie various ways to valorise plastic waste, then chemistry serves as the key to unlocking these doors (**Figure 1**). Just as Alice needs to adjust her height to fit through the door, i.e., her perspective, chemistry is crucial to rethink and reshape plastic waste into valuable resources.

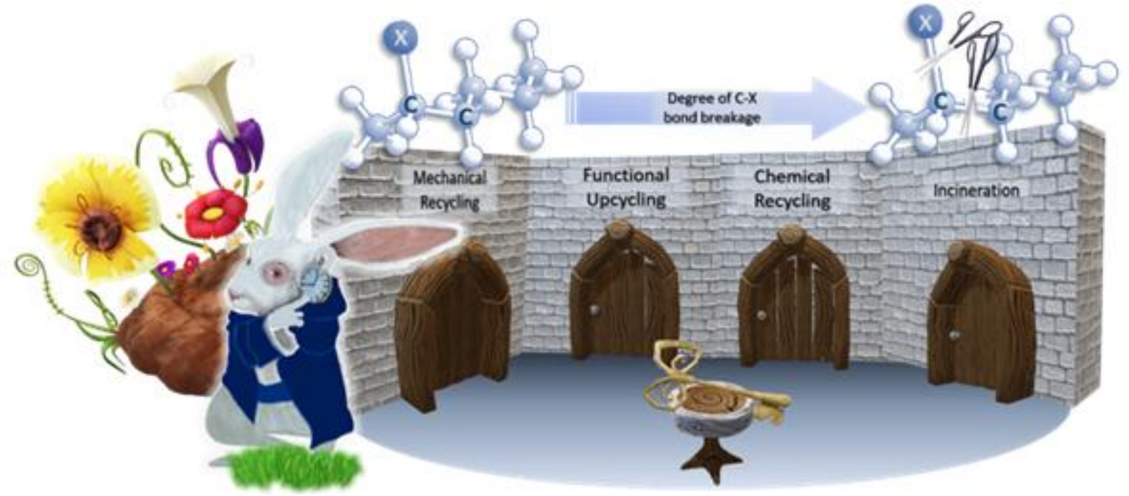

Figure 1 Down the rabbit hole of plastic fate - A Wonderland-inspired journey through polymer valorisation pathways, from mechanical recycling to incineration, mapped by the increasing degree of carbon-heteroatom (C-X) bond breakage. Functional upcycling stands out as a promising door among the options.

Polymer waste management generally falls into four categories: (i) primary (landfilling), (ii) secondary (mechanical recycling), (iii) tertiary (chemical recycling), and (iv) quaternary (incineration for energy recovery).[9] These approaches differ in terms of carbon-heteroatom (C-X) and carbon-carbon (C-C) bond cleavage (cf. Figure 1), affecting environmental impact (e.g., released microplastic/CO_2) and the quality of the recovered material.[10] Unlike landfilling, the complete cleavage of C-X/C-C bonds via incineration, provides energy recovery, but releases greenhouse gases and toxic compounds.[10] Mechanical recycling, such as grinding or re-granulating plastics, does not significantly lead to C-X/C-C bond cleavage, however polymer degradation may take place, reducing product quality.[11] Chemical recycling, on the contrary, partially breaks C-X/C-C bonds to depolymerize polymers into monomers yet it is energy-intensive and costly due to the need for specialized catalysts.[12,13] As an alternative, chemical upcycling converts polymer waste into value-added molecules or materials.[12] Guselnikova et al[10] introduced the term of functional upcycling – a paradigm that relies on post-polymerization modification and/or surface modification to introduce new functional groups while preserving the primary polymer chain, thus transforming the polymer waste into materials with tailored properties for distinct applications, all while minimizing CO_2 emissions and microplastic release.[10] By focusing on surface chemistry,[14] functional upcycling, compared to chemical recycling,[15] enhances the value of the resulting material[16] with less energy input, lower chemical and solvent cost, and reduced environmental input. Thus, functional upcycling strikes a promising balance between added value, resource utilization and environmental footprint.[10]

How functional upcycling strategies may convert the "unrecyclable" into value-added materials

Materials like tires or footwear are composed of synthetic rubber, which is a petroleum-derived elastomer.[17] Styrene-butadiene rubber (SBR), synthesized via copolymerization of styrene and 1,3-butadiene, is widely used due to its remarkable abrasion resistance and aging stability.[10] Tires are composed of natural and synthetic rubber (e.g., SBR), along with carbon black, metal, textile fabric and additives,[18] making waste tire rubber (WTR) complex and difficult to valorise. Thus, over half of SBR waste is discarded into landfills in the absence of any recycling.[10] To alleviate the end-of-life management of WTR, value-added products with tunable properties could be obtained by functional upcycling.[10] The chemical structure of SBR offers opportunities for functional upcycling; its carbon-carbon (C=C) double bonds and aromatic rings can undergo selective reactions such as electrophilic addition and substitution.[10] For instance, oxidation of the C=C bonds using as ozone[19] or nitrous oxide[20] can introduce carbonyl or carboxyl groups. Moreover, WTR modified with quaternary ammonium groups has a significantly higher capacity to adsorb nitrate and fluoride ions compared to unmodified WTR.[21] Consequently, these modifications transform WTR into multifunctional adsorbents for wastewater purification, a solution particularly valuable in resource-constrained regions. While mechanical recycling and pyrolysis remain viable, they are not always efficient for rubber valorisation. Recently, the concept of functional upcycling, especially in the context of adsorbent design, has been exploited and holds the promise to innovate WTR valorisation.[10]

A realistic outlook - the broad picture of resolving the plastic waste crisis

The Circular Economy framework emphasizes a shift from waste management to resource management, prioritizing sustainability and encouraging the reimagination of waste as a material for reuse rather than something to be discarded. To reduce the ecological and carbon footprint of plastics, a waste hierarchy should be followed, where the most preferred strategies are refuse, reduce, reuse, before even considering recycling or upcycling.[22] Still, it is not realistic to abandon plastics promptly due to unavailable reliable replacements.[23] Thus, to resolve the plastic waste crisis, plastic pollution must be addressed throughout the entire product life cycle, from design to disposal. Indeed, solving the plastic waste crisis demands collective effort from all societal sectors: citizens, industry, academia, and policymakers.[23] In March 2022, the United Nations Environment Assembly passed a resolution[24] titled "*End plastic pollution: towards an international legally binding instrument*." This resolution created an Intergovernmental Negotiating Committee to establish a global agreement on plastic pollution.[24] Nonetheless, the legal execution of this type of agreement in all countries remains uncertain.

Technological progress alone will not be sufficient to resolve the plastic waste crisis. Recycling and upcycling strategies, which are rather energy-intensive, and face challenges in real-world implementation.[23] However, the interplay between policies, technological progress and consumer behaviour can drive change, since policies can foster and adopt technological innovations, aligning with changes in consumer behaviour. Hence, multilateral policy initiatives hold the promise to collectively tackle the plastic waste crisis. Still, as individuals, we play an essential role in shaping policies, promoting innovation, and driving sustainable consumption.[23]

In the end, chemical strategies like functional upcycling are not a real-world fairy tale. These strategies represent just one piece of a larger puzzle. Still, exploring innovative chemistries in an ever-evolving, challenging environment - perhaps even with the fearless spirit of Alice, who remains wildly curious and resilient as she explores Wonderland despite the constant obstacles - could pave the way towards mitigating the plastic waste crisis.

Statement on use of AI

AI was used in the preparation of this essay solely for language correction purposes. Specifically, Grammarly was used to check for grammar, punctuation, and stylistic clarity. No AI tools were used to generate content, structure arguments, or conduct research.

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Under-18 Finalist

Biochar production: transforming biomass waste into sustainable wealth for advancing UN Sustainable Development Goals

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Introduction

Terra preta (meaning "black soil" in Portuguese) has a fascinating history that goes back to ancient civilizations in the Amazon Basin.[1] It is found in countries like Bolivia, Brazil, Colombia, Ecuador, Guyana, Peru, Suriname, Venezuela and others. Between 450 BCE and 950 CE, these civilisations utilised *terra preta* to transform the nutrient-poor Amazonian soil into fertile ground, enabling them to easily grow crops.[2] Today, we know that biochar is an important part of terra preta, and recent science has uncovered even more interesting benefits and applications for it.[3] In this essay, I'll explain how biochar (plus its byproducts, syngas and bio-oil) connects to the current UN's 17 Sustainable Development Goals (SDGs) for 2030. In this context, my work will extend regarding transforming biomass waste into valuable resources through sustainable and eco-friendly biochar production, leveraging solar power for efficiency.

Biochar production

Biochar is a carbon-rich material with a honeycomb structure. It is made through a process called pyrolysis, where organic matter, called biomass, like wood, plant waste, or agricultural leftovers, is heated in a low-oxygen environment and conditions. Ranging from 200°C to 1000°C, most of the material's hydrogen and oxygen will be removed, leaving behind a substance that's mostly carbon.[4] Pyrolysis can be done quickly or slowly depending on the desired outcome. Fast pyrolysis happens quickly and produces more liquid bio-oil, while slow pyrolysis takes longer but results in higher amounts of biochar and a byproduct called syngas.[5] It can take over couple hours and requires lower heat but produces excellent results. During the pyrolysis process, two useful byproducts are created as mentioned above. One is bio-oil, which can serve as a low-grade fuel for in boilers or car engines. The other is syngas, a mixture of gases like carbon monoxide, hydrogen, methane and small traces of other compounds. Syngas can be used to create fuel, fertilizer or even sponge iron which is a material used in steelmaking.[6,7] Nowadays, biochar is recognized as a valuable resource for sustainable fuels, improving soil health, and capturing carbon from the atmosphere.[8] In detail, biochar has the highest energy input-to-output ratio of 0.985 and 72.35% efficiency, making it the most energy-valuable pyrolysis product. With a fossil-to-energy ratio of 1.28, it ensures a net energy gain, reinforcing its potential as a scalable alternative to fossil fuels.[9]

Sustainable Development Goals

By using Google Scholar and Boolean logic over 680,000 relevant publications have been identified. The results shows that SDG 13 (Climate Action) is the most studied when it comes to biochar, syngas and bio-oil. Biochar leads at 54% because of its ability to store carbon and help fight climate change.[10] Syngas (34.8%) is mainly researched for replacing fossil fuels and cutting down on greenhouse gas emissions while bio-oil (30.5%) is explored as a renewable fuel option. SDG 15 (Life on Land) focuses on biochar (9.6%) for its role in soil restoration and sustainable farming, while syngas (16.5%) and bio-oil (28.9%) are mainly linked to energy production and industrial uses.[11] SDG 9 (Industry, Innovation, and Infrastructure) sees syngas leading at 18.7%, followed by bio-oil (12.7%) and biochar (8.6%) with all three being researched for their potential in modernizing industries and supporting green technologies.[12] SDG 7 (Affordable and Clean Energy) is another area of interest with bio-oil as a renewable alternative, syngas for clean energy applications like electricity and heating, and biochar being recognized for its biomass energy potential. SDG 8 (Decent Work and Economic Growth) looks at how bio-based resources can create jobs. Bio-oil supports jobs in refining and distribution, syngas contributes to energy production, and biochar helps with agriculture and waste management, boosting economic growth.[13] These bio-based resources also help in SDGs 1 (No Poverty), 2 (Zero Hunger), 3 (Good Health) and 6 (Clean Water). However, some SDGs, like SDGs 4 (Quality Education), 5 (Gender Equality), 10 (Reduced Inequalities), and 11 (Sustainable Cities), have less research, showing that more exploration is needed to see how biochar, bio-oil and syngas could help in these areas (see **Figure 1**). In short, when it comes to the 17 SDGs, biochar and its byproducts can be seen as eco-friendly products made from biomass. Unlike traditional products that rely on fossil fuels, biomass pyrolysis-based products come from renewable sources and help achieve net-zero carbon emissions.[14]

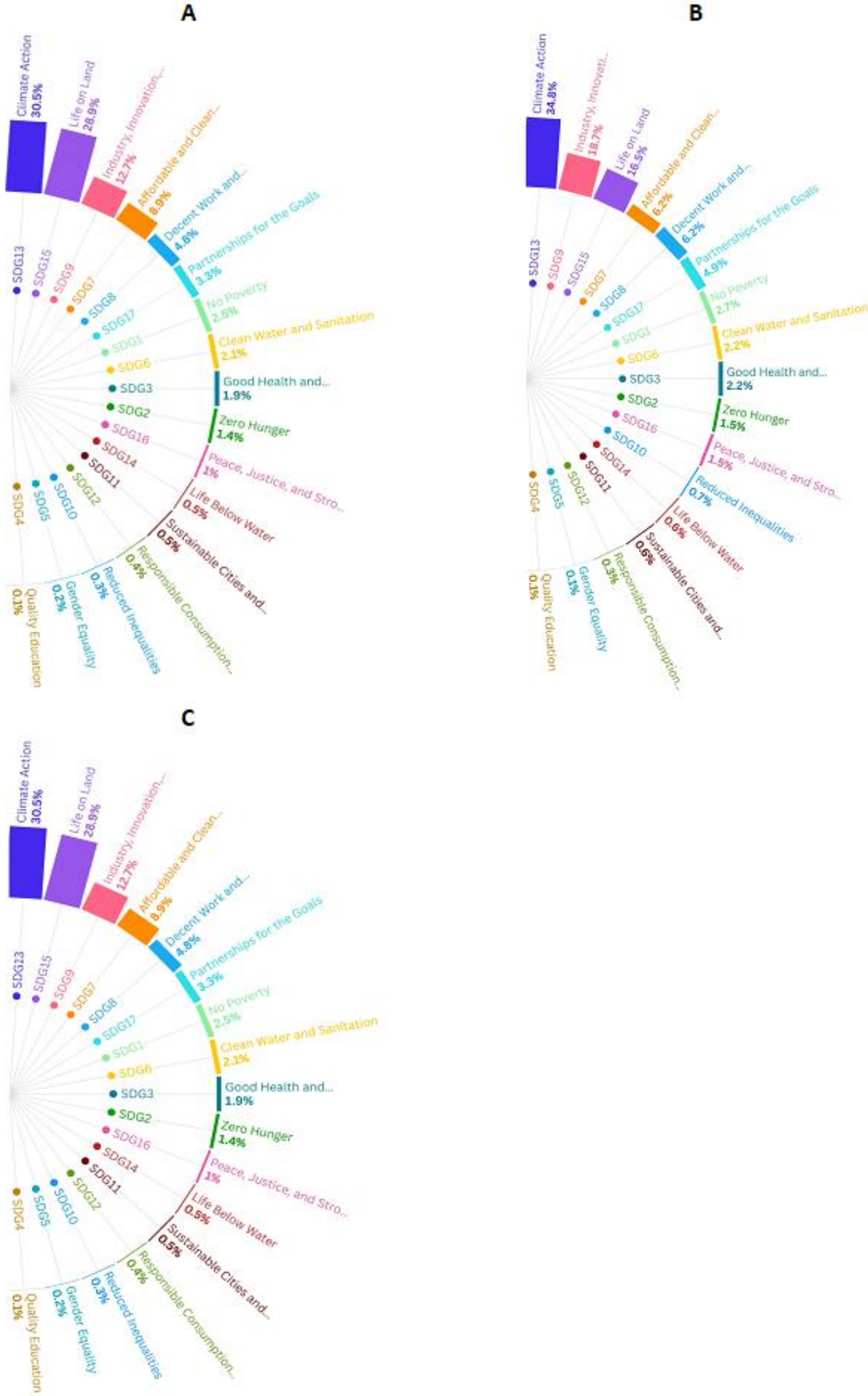

Figure 1 Distribution of publications in percentage (%) for Biochar (A), Syngas (B), Bio-oil (C) in relation to the 17 Sustainability Development Goals

Transformation of waste biomass using solar energy

Biomass is a versatile and renewable energy source that comes from a variety of organic materials, including crop residues, forestry waste, livestock byproducts and even municipal solid waste.[15] However, the way we currently handle biomass is far from efficient. Every year, the world wastes about one-third of its food supply - nearly 1.3 billion tonnes, valued at almost US$1 trillion.[16] This inefficient use of resources contributes to environmental degradation, as decomposing organic waste releases methane - a greenhouse gas 28 times more potent than CO_2.[17] With this focus, at the 2023 World Economic Forum, experts discussed on how turning biomass waste into sustainable fuels and finally can help restore the carbon balance. As climate change and fossil fuel depletion accelerate, finding cleaner energy sources is crucial. Biomass has been identified, which offers great potential, and by using advanced technology allows to harness its energy while cutting environmental impact and reliance on fossil fuels.[18] Therefore, reducing food waste and repurposing biomass efficiently are crucial steps toward achieving multiple SDGs, particularly SDG 12 (Responsible Consumption and Production) - Reducing food waste helps conserve natural resources and promotes a circular economy, and SDG 13 (Climate Action) - Preventing methane emissions from waste and using biomass more effectively can significantly reduce our carbon footprint. A promising solution to both food waste and sustainable energy lies in converting biomass waste into biochar, making it an effective tool in fighting climate change and help agriculture by hold more water and nutrients in the soil, boost crop growth, and support beneficial microbes.[19-20] However, biochar production today relies on fossil fuels and electric heating, which undermines its environmental benefits by emitting carbon dioxide. To maximize biochar's sustainability, we need to transition to cleaner energy sources for its production.[21] Solar power presents a game-changing alternative. By replacing fossil fuels with solar energy to drive the pyrolysis process, we can make biochar production truly eco-friendly and sustainable.[22] One advanced method for solar-powered biochar production involves concentrated solar power, a technology that uses mirrors or lenses to focus sunlight onto a specific point, generating extreme heat. This heat drives pyrolysis without the need for fossil fuels, eliminating carbon emissions while making the process more sustainable.[23] In detail, solar-thermal conversion helps store energy long-term in high-density fuels and valuable byproducts, boosts efficiency while cutting emissions by ditching fossil fuels, and keeps biofuels pure by preventing ash and harmful gases from mixing in.[24] By combining solar power with biomass wate, this approach creates a more sustainable and eco-friendly way to produce fuel. This shift aligns with SDG 7 (Affordable and Clean Energy) - Reducing fossil fuel dependence and expanding the use of renewable energy, and SDG 9 (Industry, Innovation, and Infrastructure) - encouraging green technologies that modernize industries and promote sustainable production methods (see **Figure 2**).

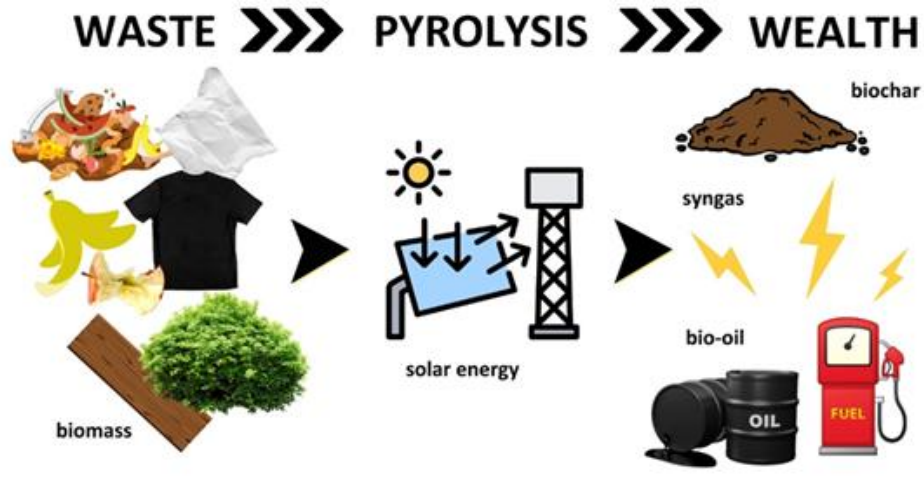

Figure 2 Proposal of turning waste (biomass) into useable and valuable resources through the process of pyrolysis powered by solar radiation (Canvas was used for designing the figure)

Conclusion

Transforming biomass waste into biochar through pyrolysis is a powerful step toward sustainability. This process converts food biomass into biochar, syngas and bio-oil, addressing climate change (SDG 13), reducing waste (SDG 12), and improving soil health (SDG 15). These byproducts also support clean energy (SDG 7) and sustainable agriculture (SDG 2). By integrating solar energy, the process becomes even more eco-friendly, cutting fossil fuel use and advancing green innovation (SDG 9). Focusing on food waste biomass turns a global issue into a sustainable solution, driving progress toward the 2030 SDG agenda and creating a more resilient, circular future. We're still in the early stages of testing this out and scaling it to an industrial level might be tricky and complex. But if we can make it work, turning biomass waste into sustainable resources could really help push forward the transformation of biomass waste into sustainable wealth.

Statement on use of AI

AI was partially used to enhance the clarity and readability of the text. It was not involved in data collection, analysis, interpretation, or in generating or plagiarizing content in any way.

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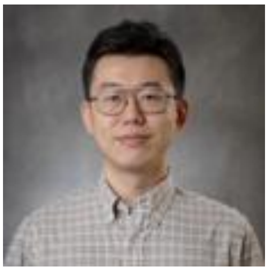
Finalist

Chemical science approach to sustainable energy solutions: recycling emerging waste from renewable energy and energy storage



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Introduction

To reach Net Zero targets, the world accelerates its transition to a low-carbon future. Therefore, energy-related technologies are experiencing rapid growth. Renewable energy sources, such as solar and wind power, are increasingly replacing traditional fossil fuel-based electricity generation, leading to significant reductions in carbon dioxide (CO_2) emissions. In 2024, global annual renewable capacity reached 666 GW, and the projections indicate an expansion to over 5,520 GW between 2024 and 2030.[1] By 2029, the electricity generation from renewables is expected to surpass coal-fired power with solar photovoltaic (PV) emerging as the leading renewable power source globally, exceeding nuclear and hydropower.[1] By 2030, solar PV is expected to contribute 34% of total renewable electricity generated, while wind power will account for approximately 30%.[1]

Batteries play a crucial role in addressing the intermittent nature of renewable energy, as well as in replacing internal combustion engine (ICE) vehicles and traditional transportation with electric vehicles (EVs) and other forms of electrified transportation, such as electric planes and ships, to reduce greenhouse gas emissions from transportation. Global battery storage capacity grew by 42 GW in 2023, exceeding 85GW, and is projected to 1,500 GW by 2030.[2] Battery storage delivers 90% of this growth, increasing 14-fold to 1,200 GW supplemented by other storage technologies, including pumped hydro, compressed air, and flywheels.[2]

Meanwhile, EV adoption continues to surge, with nearly 14 million new EVs registered in 2023, bringing the total number on the road to 45 million.[3] Lithium-ion batteries (LIBs), particularly high-nickel (Lithium Nickel-Manganese-Cobalt Oxide, $LiNi_xMn_yCo_{1-x-y}O_2$, or NMC) and lithium iron phosphate ($LiFePO_4$, LFP) chemistries,[4] dominate both EV and stationary storage applications, collectively accounting for 95% of EV battery volumes by 2030.[3]

The current stage is critical for addressing the challenge of handling emerging solar PV and LIB waste. Given the typical lifespan of these technologies, the first wave of widespread deployment in the 2000s for solar PV and the 2010s for LIBs means that their end-of-life (EOL) waste is now becoming a pressing issue, particularly in the 2020s and 2025s.[5] Proper waste management has thus become a key concern for the renewable energy and energy storage sectors.

By 2025, global solar waste generation is projected to reach approximately six million metric tons annually, with cumulative waste reaching nearly 80 million metric tons by 2050.[5,6] Disposing of decommissioned solar panels in landfills is neither safe nor sustainable, as hazardous materials such as lead and tin can leach into the environment,[5] potentially causing severe health impacts, including cancer in humans and ecosystem damage. Moreover, discarding spent solar panels in landfills is economically inefficient, as the production of new panels from raw materials is resource-intensive and costly.

At the same time, the issue of LIB waste is escalating. The cumulative EOL LIB packs generated between 2015 and 2040 are estimated to reach 21 million units.[7,8] As global demand for LIBs continues to rise, a potential supply shortfall of lithium is anticipated, with projections indicating a deficit of 2.3 to 2.45 million metric tons by 2030.[8] This underscores the urgent need for effective recycling and material recovery strategies to ensure both environmental sustainability and resource security.

State of art of emerging energy-related waste management

As the demand for clean energy accelerates, so does the need for sustainable solutions to manage EOL energy materials. Today's recycling technologies primarily focus on recovering critical materials from energy-related waste for reuse in their original applications. For instance, valuable elements like lithium, cobalt, and nickel are extracted from spent batteries and fed back into new battery manufacturing.[9,10] Similarly, silicon from decommissioned solar panels is reclaimed and purified to reach ultra-high solar-grade quality (99.9999% purity).[6]

However, meeting the stringent purity and performance standards for recycled materials required by advanced energy systems, such as EV batteries, grid storage, and high-efficiency solar cells, poses major technical and economic hurdles.

Take solar panel recycling, for example. Disassembly is a formidable barrier due to the more than 20 years lifespan of these systems.[5] Chemical disassembly, while effective, involves expensive reagents and extended processing times. Mechanical methods are faster but compromise product purity. Thermal methods increase efficiency but release greenhouse and toxic gases. Even at the purification stage, safety and environmental risks persist, hydrofluoric acid, a highly hazardous chemical, is still commonly used.[5]

Battery recycling presents parallel challenges. Variability in design across manufacturers complicates disassembly. Shredding is the dominant method, followed by separation and sorting using particle size, density, or magnetic properties.[11] Pyrometallurgy, smelting entire battery packs, eliminates the need for disassembly but results in low-purity metal alloys and low recovery efficiency.[12] To achieve reusable materials, this method must be combined with hydrometallurgy, which uses acid or alkaline leaching followed by purification steps such as precipitation, ion exchange, or electrolysis.[13] Direct recycling, a promising alternative, repairs battery materials without degrading them, but demands precise separation and sorting to maintain material integrity.[14]

Compounding the issue is the rapid evolution of energy materials. Silicon-based solar cells are increasingly giving way to thin-film and perovskite technologies, diminishing the value of traditional silicon recovery methods. Similarly, the growing diversity of battery chemistries strains conventional recycling frameworks, reducing their efficiency and profitability.

Rethinking recycling: a broader perspective

Given the growing complexity and cost of recycling energy materials for reuse in their original applications, it is increasingly clear that a broader and more innovative perspective is urgently needed. Rather than limiting recycling efforts to a one-to-one loop, where spent materials are refined and reintroduced into the same supply chain, chemical sciences open the door to a transformative, multi-loop resource utilization strategy. This approach repurposes waste materials into entirely new, high-value products across diverse industries, fundamentally redefining what it means to "recycle."

By expanding the functional destiny of these materials, we can build a more robust and adaptable circular economy, one that not only enhances sustainability but also unlocks new economic opportunities.

Take silicon, for example. Traditionally reclaimed from spent solar panels for reuse in new photovoltaic modules, waste silicon can instead be re-engineered for use in high-performance LIB anodes, where its exceptional capacity can outperform conventional graphite.[15,16] It can also be processed into nanostructured forms for use in next-generation semiconductors,[17] sensors,[18] or even as additives in advanced construction materials for improved strength and thermal resistance.[19] These new applications provide far greater flexibility and economic value, especially as the market for silicon-based solar panels gradually shifts toward newer materials like perovskites.[1]

Similarly, spent battery materials such as lithium, cobalt, and nickel can transcend their original use cases. Beyond battery production, these critical elements can be harnessed in heterogeneous catalysis for chemical synthesis,[20,21] in magnetic and electronic components,[22] or even as precursors in pharmaceutical manufacturing.[23] Repurposing strategies like these not only reduce pressure on supply chains for raw critical minerals but also create entirely new value streams from what would otherwise be costly industrial waste.

This paradigm shift, from single-loop recycling to multi-loop resource valorisation, requires interdisciplinary innovation at the intersection of chemistry, materials science, and industrial engineering. But the potential benefits are transformative: reduced environmental impact, increased resource resilience, and greater economic viability for recycling operations.

By broadening the scope of recycling to include cross-sectoral repurposing of materials, we can build a more dynamic and resilient circular economy, one that adapts to evolving technologies and markets, and turns today's waste into tomorrow's innovation.

Conclusion

As renewable energy and energy storage technologies continue to expand, the accumulation of end-of-life materials presents both a challenge and an opportunity. Chemical sciences provide a foundation for innovative recycling and repurposing solutions that extend the lifecycle of valuable resources. By embracing a multi-loop resource utilization approach, we can ensure that emerging energy-related waste becomes a valuable asset rather than an environmental burden. Through strategic waste transformation, we can drive economic growth, enhance sustainability, and achieve our long-term net-zero targets more effectively.

Statement on use of AI

ChatGPT was only used in the preparation of this essay for enhancing the language and readability of this essay.

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Finalist

Sustainable collagen-based packaging material from leather waste: green chemistry solution towards the development of zero waste disposal system

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Introduction

Plastic pollution occurring due to the unplanned management of petrochemical based single use plastic items is a major concern around the globe. Production, transportation, usage and incineration of plastic items contribute to 1.7 GT of greenhouse gas emission (GHG).[1] Moreover, the release of micro and nano plastics in the environment can cause serious concerns for living beings. Policies, strategies and solutions adopted by the countries worldwide mainly focus on recycling the used plastic items and reusing the recycled items instead of virgin plastic materials.[2–4] Despite the sincere efforts of policy makers, only 14% of plastic were recycled in Europe in 2020[5] and 12% plastic were recycled worldwide [1] which is very low compared to the huge volume of plastic waste generated every year.

Awareness and campaigns might further increase the recyclability rate of plastic items, but even after recycling and reusing, plastic items will still be responsible for higher GHG emission. Moreover, the higher fraction of the plastic item which remains untreated will be released in the aquatic environment and food chain. Hence, more emphasis should be given on finding alternatives to these single use plastic items. Biodegradable packaging material developed from natural polymers like proteins and carbohydrates, plant based natural fibres, biomass etc. can be an effective solution to this problem. Developing biodegradable and compostable packaging material will ensure that the materials are completely broken into soil after disposal, closing the loop in the waste management cycle. Collagen, a structural protein present in animals, is a popular candidate for developing green packaging material. Bovine skin is a rich source of collagen. Collagen can be extracted from unused bovine skin trimmings discarded by the tanneries using green extraction methods. The extracted collagen can be further used to develop functionalized packaging materials like edible packaging material, active packaging material and intelligent packaging material which eliminates the need for recycling after disposal.

Green chemistry solution to manage raw skin trimmings

The leather industry is considered one of the major industries responsible for the pollution of the environment due to the use of hazardous chemicals in the tanning, post tanning and finishing operations.[6] Not only the chemicals used during tanning operation but also the bovine skin trimmings and fleshing which are discarded prior to tanning operation are considered responsible for higher GHG emission even if they are managed properly through landfilling. The fleshing and skin trimmings omit around 626 kg/t CO_2 which is very high compared to the emissions from waste like wet blue trimmings, sludge, hair, shavings, buffing dust etc.[7] Higher carbon footprint, use of hazardous pollutants, excessive freshwater consumption in tanning baths as well as disturbance in biodiversity due to environmental pollution associated with the leather making raises concern regarding the achievement of sustainable development goals (SDG) proposed by the United Nations (UN).

Following the restrictions from buyers and consumers some of the tanneries around the world have adopted an environmentally friendly leather making approach for ensuring accountability, traceability and authenticity. Around the globe this approach is closed monitored and certified by the Leather Working Group (LWG). The LWG certification process has well established sections for the effective management of solid waste and most of the tanneries choose landfilling as a viable option for the management of skin trimmings. Despite the sincere efforts to manage it in within a well-built solid waste disposal system, it still poses the risk of GHG emission.[7] Moreover, trimmings are sometimes unethically used as poultry and fish feed which might be responsible for heavy metal accumulation in the human body. Thus, to develop a carbon neutral world a sustainable and economically viable solution is required to manage skin trimmings.

Bovine skin trimmings contain 21.5% Type I collagen which is a major structural protein present in mammalians and has triple helical structure formed by amino acids.[8] Collagen has stability, strength, as well as biocompatibility and can be used to develop various types of functionalized material.[8] Green chemistry can play an important role in extracting collagen from animal skin trimmings. Traditionally, collagen is extracted from leather waste using harsh chemicals like acetic acid and sodium hydroxide. Collagen can be extracted from trimmings through enzymatic hydrolysis which is a green approach contrary to the traditional chemical-based methods since it only utilizes crude enzyme as the hydrolysing agent (**Figure 1**).

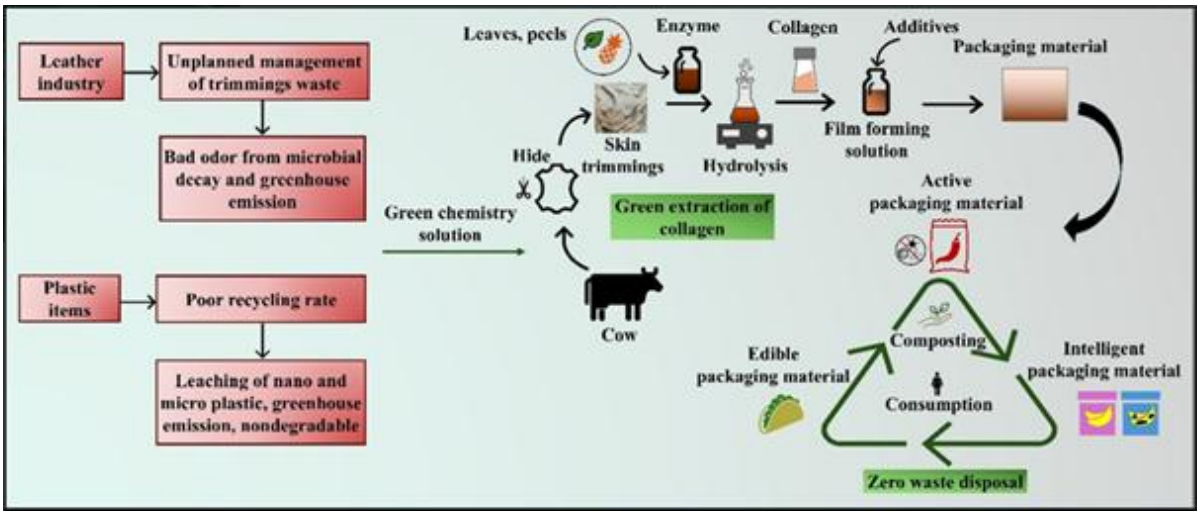

Figure 1 Plant-based protease enzyme-assisted collagen extraction for developing sustainable packaging materials to address issues with plastic pollution and unplanned management of leather waste

Proteolytic enzymes have strong specificity for collagen and can separate it from the extracellular matrix. Collagen can be extracted using plant based proteolytic enzymes: papain,[9] bromelain[10] and ficin.[11] Papain enzyme is sourced from papaya leaves; bromelain is collected from pineapple peels and ficin is extracted from fig leaves which indicates that proteolytic enzymes are mostly sourced from renewable sources. Moreover, most of the enzymes are extracted using water as solvent and are used in its crude form. Enzyme purification requires an extensive set of chemicals and is usually a very delicate and time bound process. Utilizing enzyme in its crude form reduces the chemical usage, time and cost associated with the purification process. Enzymatic hydrolysis method is reported to be way more effective in extracting collagen, can reduce the GHG emission as well as is cost effective compared to other methods since energy consumption, time and resource utilization are reduced in crude enzyme-based hydrolysis methods.[9]

Collagen-based packaging materials: an alternative to plastics

Collagen along with different additives like thickening agents, antimicrobial agents, crosslinkers, antioxidants, plasticizers, and indicators are utilized to develop packaging materials through solvent casting method. Collagen has been used in various types of sustainable packaging material- green packaging material,[12] edible packaging material, [13] active packaging material,[14,15] intelligent packaging material.[16,17] Edible packaging can be consumed along with the food items, but it is necessary to evaluate the cytotoxicity profile of the ingredients before consumption. Active packaging extends the shelf life of the stored food products and intelligent packaging provides the opportunity to monitor the freshness of the stored food items. Moreover, these packaging materials offer improved performance in terms of tensile strength, thermal stability, UV resistance, water vapor permeability, hydrophobicity, and antibacterial properties.

Collagen based packaging materials offer robustness, functionality and biodegradability which makes them a suitable alternative to traditional plastic items. Moreover, they help to establish the zero-waste disposal system by eliminating the need for incineration and landfilling. Collagen based packaging materials are either consumed with food or used as compost for soil after disposal (**Figure 1**). Due to having nitrogen-rich compound like collagen (collagen contains around 16-18% nitrogen) in its matrix,[9] the packaging material can help to improve the fertility of the soil. The improved fertility will ensure higher crop yield, and the crops can be used as food items for the animals like cow and goat. This kind of circular economy approach ensures that green strategies are adopted in each step as well as the resources are reutilized throughout the cycle with minimum waste being generated. Adopting green strategies in waste valorisation process ensures that the overall GHG emissions are reduced. Moreover, effective and efficient utilization of both renewable and non-renewable resources as well as waste materials helps to overcome the issues regarding resource depletion and scarcity. This in turn creates a positive impact on climate change and ensures the sustainable consumption of resources. Thus, the waste valorisation approach developed through green chemistry-based innovation can help to achieve the 11th and 13th sustainable development goals known as "Responsible consumption and production" and "Climate action".

Conclusions

Collagen extracted from leather waste through enzymatic hydrolysis can act as a valuable biomaterial and can be used to develop functionalized packaging material. This waste to wealth approach ensures the responsible consumption of resources, paves a way for generating economic returns and saves the environment from pollution through sustainable management of solid waste. Bioplastics developed from collagen offer unique combination of sustained performance and enhanced degradability in soil. Despite having superior performance compared to plastics, the only thing that limits the commercialization of collagen-based packaging materials is the higher cost associated with its fabrication technique. Hence, more detailed research work and industry-academia collaboration is required to make it affordable like traditional plastic items. By incorporating green chemistry in real life problems, endless opportunities like this can be created which ensures the reduction of harmful chemical usage, enhances the use of plant and animal derived components and promotes the fabrication of biobased materials. Technologies like artificial intelligence can be further incorporated along with such green strategies to predict models which can offer better understanding of the system and thus can result in delivering better outputs.

Statement on use of AI

The author declares that AI and AI based tools were not used in preparing this essay.

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Finalist

Ensuring a secure and sustainable supply of phosphorus: the need for fostering environmental and socioeconomic sustainability in the transformation of waste streams into resource streams

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The human population undergoes continuous growth since the end of the Black Death in the 14th century, totaling 8.2 billion as of 2024; and is projected to reach 9.7 billion and 10.2 billion by 2050 and 2100, respectively.[1] As population pressure increases, more efficient food production systems have been developed to ensure food security. Crucial developments for food production have been achieved along the history of humankind, from the domestication of plants and cereals in the Neolithic Revolution (*circa* 11500 - 8000 BP),[2] the introduction of irrigation systems, crop rotation and animal-drawn ploughs by antique civilizations (*circa* 500 BC – 600 AD), and the implementation of the three-field system since the 8th century;[3] to modern agriculture techniques boosted by the mechanization of agriculture and development of intensive farming practices in the 19th and 20th centuries.[4,5] Among the advances achieved in the late modern period, the industrial production of nutrients was crucial to support the development of the Green Revolution in the 20th century.[6] The development of the Haber-Bosch process for the production of synthetic nitrogen-based fertilizers and industrial processing of phosphate rock in the late 19th and early 20th centuries improved the productivity of agriculture and farming industries, ensuring food security in many regions in a context of rapid population growth.[7]

Despite modern agriculture techniques having undoubtedly increased the yield of food production, multiple environmental threats have emerged as a consequence of intensive farming practices, including the emission of greenhouse gases, soil degradation, and water scarcity, among others. With regards to the use of industrially processed phosphorus, there is evidence that the natural cycle of phosphorus has been altered by the generalized application of mineral fertilizers on croplands. Notably, in certain locations vast amounts of mineral phosphorus are released into the environment from the over-application of synthetic fertilizers and livestock manure, building up a phosphorus legacy that leads to the eutrophication of the aquatic ecosystems.[8]

However, the concerns derived from the widespread use of mineral phosphorus fertilizers are not limited to the environmental dimension. Since phosphorus is a non-renewable, limited resource with no synthetic substitute known, a geopolitical facet of the problem arises over the control of Earth's limited and unevenly distributed reserves of this crucial element for food production. As a consequence, many countries rely on global phosphorus supply chains vulnerable to be disrupted.[7] Additionally, there exist regional imbalances on the access to phosphorus fertilizers, compromising the global nutrient equity.[9] Considering the phosphorus challenges described, the development of a circular phosphorus economy addressing the recovery and recycling of this element is not only desirable, but necessary to ensure food security within a sustainable agricultural paradigm.

The adoption of a circular phosphorus economy must mitigate the environmental footprint of intensive agricultural practices without compromising food productivity. Moreover, it must be financially and socially viable to avoid the emergence of deprived social groups bearing the economic burden of this new paradigm.[10] As such, the circular phosphorus economy should capture the local environmental and socioeconomic contexts to deliver tailored solutions to the needs of each region, but it should be also framed within the national food security strategy for securing a reliable phosphorus supply.

To restore the phosphorus loop, it is essential to recover the phosphorus used in different anthropogenic activities and reintroduce it into the food production system. Viable material flows have been identified as suitable for phosphorus recovery. These flows mainly belong to the production, consumption, and disposal of food; including livestock manure, food waste, and municipal wastewater.[11] The land application of manure as fertilizer for crops has been an historical practice for the recycling of phosphorus,[6] and it is still a common practice today.[12] However, the development of modern intensive agricultural techniques have altered the natural cycle of phosphorus, decoupling large-scale livestock operations, phosphorus-rich organic waste, and croplands. Consequently, the phosphorus loop is reshaped in a one-direction flow through a process that has been defined under the concept of "metabolic rift".[13] Therefore, phosphorus contained in crops and livestock products is not recycled but wasted in lakes and oceans. As a result, virgin phosphorus rock is mined and processed to obtain the fertilizers used to supply the required nutrients to croplands.

Although different processes have been proposed for the recovery and recycling of phosphorus, as well as for its redistribution from saturated regions to phosphorus-deficient areas, achieving a feasible circular phosphorus economy also requires consideration of social and economic sustainability. In this regard, one of the main challenges is that the cost of recovered phosphorus-based fertilizing materials is significantly higher than phosphorus mined-based fertilizers.[11] However, to gain complete understanding of the economic dimensions of phosphorus utilization, we must also consider the hidden effects associated with its end-of-life. These effects include the costs associated with the environmental and economic damages caused by the uncontrolled releases of phosphorus into the environment, and the need of mining virgin phosphate rock to substitute the phosphorus lost by organic waste disposal. Once the end-of-life costs are considered, which were estimated at 74.5 USD (2020) per kilogram of phosphorus released,[14] the financial sustainability of the circular phosphorus economy seems to be guaranteed.

However, although a circular phosphorus economy might be economically sustainable in macro-economic terms, it is questionable whether it can be economically sustainable for the stakeholders affected. The implementation of systems for phosphorus recovery involves additional investments and operational costs, but it remains unclear who should face these costs. Phosphorus recovery might be financed through an allowances system for the release of phosphorus, where the emitters of phosphorus should purchase rights (or credits) that would allow them to release phosphorus to the environment. Although an allowances system would incentivize them to recover phosphorus to avoid the cost of purchasing such rights and to earn revenues from the unused rights that can be sold to other emitters.[15,16] However, it is arguable that these approaches may endanger the financial sustainability of enterprises, or that they might result in charging the cost of phosphorus recovery to the consumers, hindering their access to food. Moreover, previous studies highlight the important role of the economies of scale in the cost of phosphorus recovery, which would lead to unfair systems where the small-scale stakeholders bear a larger economic burden in relative terms than large-scale stakeholders, even though the former represent a larger environmental threat due to their scale.[17]

Some pioneering efforts are addressing the economic challenges described above and the adverse social impacts that they could entail. At a regional scale, some of the initiatives proposed include the development of coordinated markets for efficient phosphorus management, conciliating phosphorus in-excess releases and demands while minimizing the capital and operating costs of the system.[18] Another approach is the implementation of water quality trading schemes at the regional level. Through these systems, small-scale wastewater treatment plants lacking the economies of scale to achieve cost-effective phosphorus recovery comply with their discharge limits by funding more efficient phosphorus capture systems from other sources within the same watershed.[19] Other initiatives are directed to study the economic effects of phosphorus recovery from wastewater on the communities served by these facilities. Significant variations in cost of phosphorus recovery have been identified between urban and rural areas due to the diverse levels of treatment and scale of wastewater resource recovery facilities, as well as to the regional differences in the average per capita annual income.[10] As a result, inter-regional cooperative policies will be required to distribute the economic burden of phosphorus recovery to avoid the rise of deprived social groups as a consequence of the transition toward a circular phosphorus economy. To address this imbalance, scale-sensitive incentive policies to distribute the cost of phosphorus recovery among emitters should be explored, preventing some stakeholders from bearing a larger economic burden than others due to their size. Another aspect to be addressed is the fair allocation of incentives to balance the economic impact of phosphorus recovery among stakeholders of multiple scales.[17]

Finally, it is worth noting that despite the multidisciplinary efforts devoted by the academia and industry seeking to overcome the technical, environmental, financial, and social challenges of restoring the phosphorus loop, it is crucial to raise awareness at every level about the phosphorus challenge. The engagement of all stakeholders, from individual citizens to governmental decision makers, is essential to develop a credible, fair, and sustainable circular phosphorus economy.

Statement on use of AI

No AI was used in the preparation of this essay.

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Finalist

Transforming carbon dioxide from waste into an economic asset for a sustainable future

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In 2024, atmospheric carbon dioxide (CO_2) levels averaged a record high of 421.73 ppm, exceeding pre-industrial levels by over 50%.[1] This concerning milestone underscores the importance of efforts to make use of CO_2 in addition to reducing its production. Increasing levels of carbon emissions, agreeably due to global dependence on fossil fuels for energy, have been accompanied by global warming, arctic changes and ocean acidification.[2] Higher CO_2 concentrations would significantly increase imbalances in the ecosystem and cause long-term shifts in weather patterns which would affect the quality of life.[3] In response to this threat, many governments have established international agreements considering the importance of Carbon Capture, Utilization and Storage (CCUS) in limiting severe climate change.[2] In CCUS, a high-purity CO_2 stream is extracted from fossil fuel combustion exhausts and converted to valuable products, leading to resource recovery. Capturing CO_2 from emission sources decreases its levels directly without requiring extensive changes in current processes and infrastructure, which would need significantly more time to execute. Accordingly, many policies like financial benefits and research funding for CO_2 capture and storage have been implemented in countries like the United States and China.[4] In addition, strict environmental regulations and carbon pricing systems that place a monetary value on greenhouse gas emissions have been established to compel industries to lower their carbon footprint.[4] Unfortunately, even with these incentives and rules, there are still many barriers to large-scale implementation of CCUS technologies.

Despite the known drawbacks of fossil fuels, they retain popularity due to their accessibility, efficiency, portability and cost-effectiveness.[5] As their extensive use continues to raise CO_2 levels, CCUS remains a critical part of attaining carbon neutrality. Carbon utilization faces challenges partly due the molecular thermal stability of CO_2, which requires high energy to break its chemical bonds for conversion and necessitates innovative catalysts to increase reaction rates.[4] Linking CO_2 utilization to highly-relevant products increases the burden to optimize catalysts and overcome implementation barriers. The chemical sciences are instrumental in strengthening this link by finding viable methods to convert CO_2 to useful and value-added products. There can be several economic advantages to developing efficient routes from CO_2 to materials of high demand even beyond environmental remediation. CCUS is currently being outpaced by emissions because many CO_2 conversion methods are costly in addition to being energy intensive,[6] but there have been many chemical advances. The development of novel techniques and the optimization of current systems can make CO_2 conversion more feasible at the industrial level.[2]

One of the approaches to CCUS is to use energy from renewable sources like solar, wind, wave and nuclear to synthesize high-density fuels from captured CO_2.[5] This approach promotes a sustainable route to carbon circularity in the energy sector. It also allows for renewable energy to be harvested into energy carriers whereas sources being located far from areas of consumption limits complete dependence on them.[5] Approximately 5-10% of CO_2 emissions can be used for the production of fuels and chemicals, but fuels have a much higher worldwide consumption.[7] However, the availability of these fuels from other sources lessens the drive to reproduce them from CO_2 emissions. Liquid hydrocarbons are currently primarily produced from low-cost crude oil and partly from coal, natural gas and biomass, with an overall demand of millions of barrels a day in the United States alone.[8] While there are many short and long-term benefits of transitioning to carbon feedstocks for energy production, there is less of a demand to do so. Even more, the use of these fuels immediately re-emits CO_2 back into the atmosphere, still contributing to climate change. Using CO_2 to produce valuable chemicals in other sectors in addition to fuels has the potential to have a great impact on the carbon economy.

Research in the chemical sciences has led to the discovery of CO_2 conversion routes to relevant feedstocks in chemical, pharmaceutical and polymer industries.[4] Common CO_2 products that have been investigated include urea, polyurethane, inorganic carbonates, and polycarbonates, which all individually have a demand of over 5 million tonnes a year.[4] Already, roughly 130 metric tonnes of CO_2 are being used to manufacture these chemicals, with urea production consuming the most industrially produced CO_2 waste.[9] There have been many noteworthy recent developments in the production of these chemicals that increase their potential for a surge in worldwide implementation, some of which will be elaborated on below. Studies to understand reaction mechanisms and structural effects of catalysts have led to improved viability through higher efficiencies.[2-4,6,7]

Urea is a neutral and non-toxic fertilizer that is rich in nitrogen and is easy to store and transport.[10,11] It is also used as a raw material for the synthesis of plastics, anticancer agents, resins, explosives and adhesives.[3,6,10] Thus, it is widely depended on for its significant contribution to the agricultural, medical and chemical sectors. Industrial urea synthesis mainly involves the production of ammonia (NH_3) through the Haber-Bosch process then urea through the Bosch-Meyer process.[11] Both of these processes operate under harsh temperature and pressure conditions that rely on immense fossil fuel energy and lead to net CO_2 emissions. Over the years, many new routes for urea production with reduced emissions and lower environmental risks have been proposed. One particular method directly utilises CO_2 and enables direct urea synthesis without intermediate NH_3 production. The electrocatalytic reaction of nitrogen (N_2) and CO_2 via C-N bond formation or coupling is a gamechanger.[11] This is mostly because both reactants are chemically inert under normal conditions, and it is very difficult to construct or activate a C-N bond. A 2020 study used a palladium-copper electrocatalyst to couple N_2 and CO_2 in water at ambient conditions to produce urea at a high rate but with low faradaic efficiency due to side reactions.[12] Studies of the separate steps, mechanisms and intermediates in this reaction have led to progress in the design of the process. While it remains a challenge to balance high yield and high efficiency, this C-N coupling has high scalability and great potential to meet industrial application demands.[11]

CO_2-based polymers formed from the copolymerization of CO_2 with hydrocarbons have attracted much interest because of their potential to be environmentally friendly.[2,4] They can also reduce petrochemical consumption as many monomers for polymerization are derived from refined petroleum. Though the use of CO_2 for polymers was reported as early as 1969, it faces challenges like low catalytic activity and poor physical properties of products.[4] Many studies have been conducted in recent years to better understand and improve the copolymerization system. In 2011, a pilot plant was opened in Germany to produce high-quality CO_2-based plastics like polyurethane under a project called "dream production", which shows industrial feasibility.[3] Polyurethane is a highly versatile polymer used in thermal insulation, footwear and furniture among many other applications. To facilitate commercialization of CO_2-based polyurethane, many strides towards higher yields and green reagents and intermediates are being made. Research into the synthesis of isocyanate, a key monomer conventionally produced from a highly toxic material, has led to an alternative route that reduces emissions by 16.1% with 22.76% improved environmental benefits.[13] In addition, improvements in catalyst design have led to higher yields and better efficiencies through the reduction of side reactions.[13] There is great potential for the sustainable industrial production of polymers even beyond polyurethanes to reduce dependence on fossil fuels.

Urea and polyurethane production are evidence that transitioning to CO_2-derived chemical products is attainable. There have also been many advances in the production of inorganic carbonates[4] (construction components), polycarbonates[2] (amorphous thermoplastics) and salicylic acid[3] (a pharmaceutical component) from CO_2. As a plethora of potential conversion pathways continues to emerge, it is essential to identify which ones are viable for short to mid-term deployment.[9] For these products to become preferred over their fossil fuel-derived counterparts, these breakthroughs must reach beyond the scientific community to garner industrial approval. The global feasibility of CCUS processes must be studied and monitored by more publications and social channels.[9] Awareness of and attention to these technologies can be increased by public awareness in order to influence their implementation and support political strategies.

In summary, the current projection of the future state of our planet demands the prioritization of mitigating atmospheric levels of CO_2 through CCUS. The chemical sciences continue to make large strides in developing viable routes to value-added products of high demand. These efforts must be accompanied by an increased commitment by policymakers, communities, industries and individuals to promote and facilitate their establishment. CO_2 becoming a valuable and demanded resource can lead to a greener and more sustainable future.

Statement on use of AI

No AI was used in the preparation of this essay.

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Finalist

Chemical sciences as key enablers in unlocking the potential of e-waste for a sustainable and eco-friendly future

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Electronic devices have become an integral part of modern society, simplifying lifestyles and driving advancements in multiple sectors. However, the rapid consumption and disposal of electronic products have resulted in an increasing electronic waste (e-waste) crisis. In 2022, 62 million metric tons (Mt) of e-waste were generated globally while only 13.8 Mt is recycled.[1] With this trend, a rise to 82 Mt is projected by 2030, which will certainly have devastating consequences to the ecosystem and global economy. This underlines the need for serious commitment from stakeholders and more efficient and sustainable e-waste processing techniques. Reversing the growing trend by revitalizing the circular economy (CE) model into the e-waste context is essential by pushing innovations in chemical science and engineering along with proper policies and public awarenesses. The CE strategy emphasizes the necessity of resource and waste minimization by avoiding, slowing and reducing energy and material loops by using skills from chemical science and related disciplines.[2] Incorporating CE with e-waste processing plays critical role towards achieving full utilization of e-waste to wealth by minimizing the amount of electronic discards, recovering valuable materials and reducing environmental and health risks.

There are three common stages in e-waste recycling: e-waste collection, sorting and dismantling, and finally end-processing stage to recover components.[3] It becomes critical to utilize the full potential and prospects of chemical sciences into all the stages of e-waste recycling to effectively shift the use-and-throw mindset prevalent in the disposal of obsolete electronics. For instance, proper identification of potential hazardous components and safe handling is essential at the collection stage which can be possible with the knowledge of chemical properties and attributes of e-waste components. Taking actions such as toxic component immobilization during e-waste storage and transportation can be realized through novel encapsulation design, highlighting the possible intervention from chemical science.[4] Additionally, expanding skill and knowledge of hazard mitigation and e-waste handling through regular training at the collection centres is crucial for comprehensive adherence towards safe and sustainable e-waste management. During the sorting and dismantling stages, there are needs for further simplification and customization to enhance the feasibility of e-waste recycling. For example, chemical science approaches can enable efficient classification of e-waste components based on their elemental composition using chemical and spectroscopic sensor-based sorting.[5] On the other hand, e-waste dismantling may damage valuable materials which have high economic value and potential for new material developments. Proper understanding of e-waste chemistry helps to effectively design solutions. By applying knowledge from thermodynamics, one can propose thermal or chemical activation of selected e-waste for weakening bonds between components which can lead to easier disassembling without significant damage. Furthermore, mastering concepts across chemical science helps to develop algorithms for machine learning to improve sorting accuracy, reduce processing time and avoid manual errors. **Figure 1** shows a simplified schematic illustrating the discussed concepts in each stage where contribution from chemical sciences (CS) is a key to achieve a feasible and safe e-waste recycling process. It also highlights conventional e-waste disposal (route A), which harms human health and the environmental ecosystem while causing significant loss of valuable resources. As shown in the diagram, e-waste comprises different components. Metals constitute huge portion of e-waste (60%) followed by plastics such as polystyrene (PS), polyvinyl chloride (PVC) accounting to 15% and metal-plastic mixtures (5%).[6] The high proportion of critical metals and plastics in e-waste necessitate the development different e-waste recycling approaches such as chemical, mechanical and biological methods.[7] However, the current approaches need to be more efficient and feasible to comply with the CE strategy.

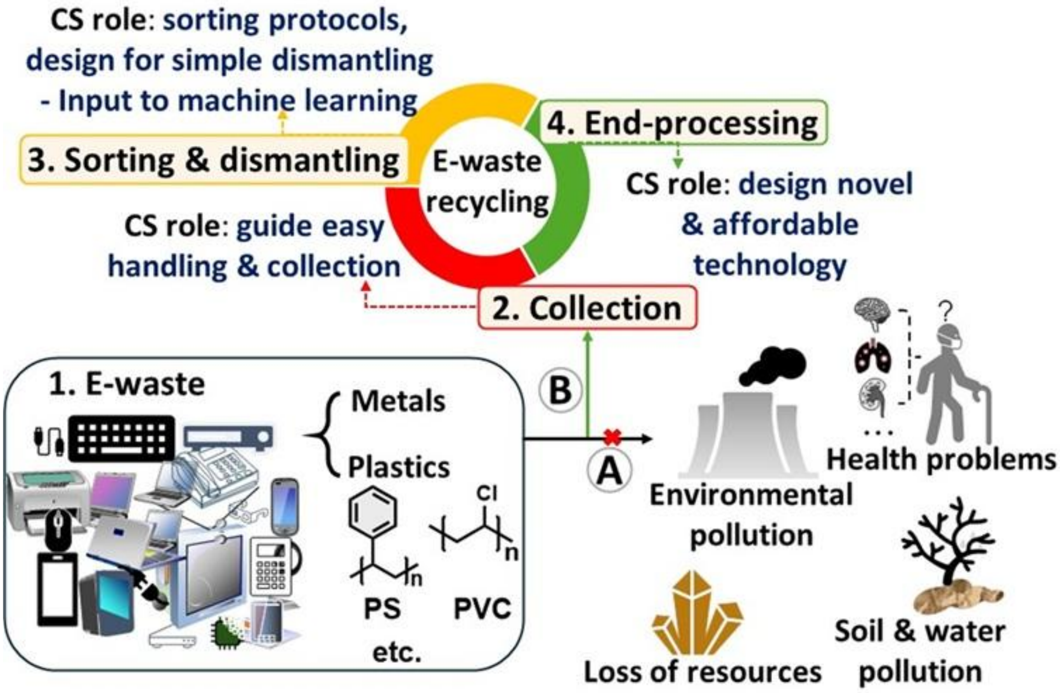

Figure 1 Schematic showing linear e-waste disposal and its risks (route A) versus a circular strategy with proposed interventions from chemical sciences (CS) at each recycling stage (route B)

Therefore, the end-processing step of e-waste is critical to effectively recycle targeted components and to keep the waste disposal threshold at a minimum. At this stage, chemical sciences play a pivotal role in designing e-waste recycling processes that are eco-friendly, less energy and capital intensive, and standardized for feasible product development. In reprocessing the waste, input from green chemistry principles is inevitable for environmentally benignity and safety. Conventional e-waste recycling is mainly made through chemical methods. Experts equipped with chemical sciences enabled the development of biological methods by using microorganisms to recover precious metals without generating toxic waste.[8] The biological method is advantageous in terms of cost effectiveness and environmentally friendliness. Prevention of water and air pollution is also viable by lowering emissions using closed loop system. Additionally, energy efficient e-waste processing is possible through chemical innovations such as favouring less temperature processing and effective sorting for accurate separation of e-waste components.

Many of the current e-waste recycling processes are energy-intensive, unsafe, and inefficient, leading to environmental and economic challenges.[9] As shown in **Figure 2**, effective collaboration among stakeholders is crucial to harness the full potential of chemical science and further advance in transforming e-waste into valuable resources while minimizing its environmental impact. In this regard, openness to cross-discipline learning, use of data-driven intelligent systems to accelerate and optimize e-waste processing, and proper awareness are key factors. Additionally, researchers and academic institutions should develop advanced recycling technologies and integrate sustainable waste management into their curricula to produce skilled professionals. Global partnerships between researchers and institutions are essential to achieve shared goals. Electronic manufacturers need to adopt greener methodologies, design eco-friendly, recyclable products and establish waste recovery systems. Governments and policymakers should work with academia to create and enforce sustainable e-waste legislation, promote a circular economy, and encourage manufacturers to invest in recycling through extended producer responsibility. Furthermore, governments can offer tax incentives, support brands using recycled materials, and encourage consumers to return old devices with discounts on new ones. By doing so, the ecosystem benefits from reduced pollution, while societies entertain improved well-being and cost savings. Furthermore, optimizing e-waste recycling opens new opportunities for emerging applications. These include advancements in energy conversion and storage systems, biofuel production, recovery of precious metals, and development of advanced electronic components.[10-13] By refining e-waste recycling methods through innovations in chemical science, we can not only minimize waste but also create valuable resources.

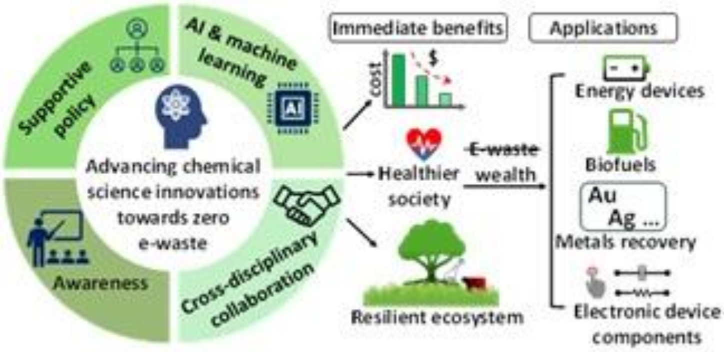

Figure 2 Key factors to accelerate and implement innovations in CS (left). Possible benefits and emerging recycled e-waste applications by utilizing CS approaches (right)

In conclusion, the current methods of handling and processing e-waste are neither sustainable nor efficient, and the level of attention given to this issue globally remains inadequate. E-waste generation is rapidly increasing, posing serious environmental and economic challenges that require immediate action. Addressing this crisis demand boosting chemical science innovations along a collective effort from key stakeholders, including academic and research institutions, industries, governments, and policymakers. Swift and strategic initiatives must be implemented to align with the 17 Sustainable Development Goals (SDGs), ensuring a responsible and circular approach to e-waste management. To achieve this, e-waste processing must adhere to strict sustainability standards, embracing greener technologies, zero-waste and effective recovery approaches. Additionally, end-of-life applications must be integrated into material design and upscaling strategies by applying science and engineering skills, ensuring that products are created with recyclability and resource recovery in mind. By adopting these measures, it becomes evident that e-waste will no longer be seen as a danger but rather as a valuable resource for generating wealth.

Statement on use of AI

No AI was used in the preparation of this essay.

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Finalist

Valorising agro-industrial waste: by-products as a sustainable source of bioactive compounds and biomaterials

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The environment has been increasingly affected by unsustainable human activities, population growth, and climate change which have led to profound changes in global ecosystems and have exacerbated the depletion of already limited natural resources.[1] These factors have also led to an increase in agro-industrial production to meet the growing demand for food and other products for human consumption, consequently resulting in an escalating agro-industrial waste generation.[2] The generated agro-industrial waste encompasses a diverse range of by-products from the food and agricultural sectors which are produced in substantial quantities, approximately 1.3 billion tons of waste per year.[3] The stages of transportation, storage, and processing within the agro-industrial production chain significantly contribute to the generated waste which includes various plant parts such as leaves, stems, stalks, roots and seeds, fruit peels, as well as spent grains and husks.[4,5] The disposal of this waste through conventional methods such as incineration, open dumping, and inadequate landfill practices is currently harmful to the environment, generating greenhouse gases and pollutants, degrading soil health, and exacerbating climate change.[2,3] For instance, the carbon footprint associated with agro-industrial waste equates an annual accumulation of 3.3 billion tons of CO_2 in the atmosphere.[3] Therefore, proper disposal is important to reduce the environmental impact of agro-industrial waste. On the other hand, these by-products also hold significant potential for valorisation and are attracting growing interest due to their rich chemical composition.[3]

Agro-industrial by-products have been extensively studied to assess their potential for obtaining new bioactive compounds or replacing existing ones whose production poses environmental risks.[6] Upcycling involves transforming industrial by-products into new and higher-valued products that would otherwise be discarded, promoting the reduction of waste as well as a more sustainable and circular economy.[7] Bioactive compounds obtained through upcycling have become highly important across several industries, including cosmetics, dietary supplements, functional foods, and pharmaceuticals. Agro-industrial by-products can be a rich source of valuable bioactive compounds, including proteins, vitamins, fatty acids, amino acids, dietary fibres, terpenoids, thiols and phenolic compounds.[8] Some relevant phenolic compounds include anthocyanins, catechins, flavonoids, isoflavones, lignans, and tannins, along with terpenoids, such as carotenoids, capsaicin, and phytosterols, and thiols, which consist of organosulfur compounds. The bioactive compounds extracted have been reported to offer various health benefits, largely attributed to their antioxidant and antimicrobial properties.[8] In addition to bioactive extracts, the valorisation of agro-industrial waste for sustainable biofuels and packaging solutions, such as bioplastics, has become a widely adopted strategy which offers biodegradable alternatives to conventional materials.[9]

Various strategies have been employed to treat and valorise agro-industrial waste converting it into biofuels, such as biomass, bio-oil and biogas. These strategies encompass biological and thermochemical conversion methods, as well as advanced hybrid technologies.[9] Specifically, biological processes like anaerobic digestion, alcoholic fermentation, photobiological techniques, and transesterification via enzymatic catalysis are used.[9] Thermochemical conversion methods include torrefaction, pyrolysis, gasification and liquefaction.[9]

The sustainable extraction of bioactive compounds from agro-industrial waste can be achieved by applying green chemistry principles, in addition to conventional extraction methods like hydrodistillation, maceration, and solvent or Soxhlet extraction, which use organic solvents and need specific temperature and agitation conditions.[7] A more sustainable extraction involves using solvents with lower environmental impact, employing biocatalysis, and implementing efficient processes that reduce waste, energy consumption, and the number of synthesis steps. Several innovative methods have been used to extract bioactive compounds from agro-industrial by-products, including enzymatic processes, solid-state fermentation, ultrasound-assisted extraction, microwave-assisted extraction, supercritical fluid extraction, pressurized liquid extraction, subcritical water extraction and the use of deep eutectic solvents.[6,10]

An example of upcycling agro-industrial waste includes extracting bioactive compounds from cork by-products and converting it into cosmetic ingredients. Notably, cork powder, a by-product produced in large quantities by the cork industry, has primarily been used for energy production, however, this application alone is insufficient to handle the entire volume produced.[11] Therefore, studies have investigated the potential of cork powder as a pigment in decorative cosmetics and as a source of bioactive compounds, namely flavonoids, coumarins and ellagitannins, for use in the nutraceutical, pharmaceutical, and cosmetic industries.[12-14]

Another example of valorising agro-industrial waste is the use of coffee by-products. In the production of instant coffee, only a portion of the coffee beans is used to produce the beverage, leaving behind a significant amount of spent coffee grounds as a by-product.[15] This coffee by-product has been investigated for biodiesel production via transesterification processes.[16] Additionally, it has been used to extract bioactive compounds, including caffeine, polyphenols, and chlorogenic acids, through green chemistry extraction methods such as ultrasound-assisted and microwave-assisted extraction.[15, 17] These compounds have also the potential to be used in many industries related with health and personal care products.

Nevertheless, the upcycling of agro-industrial waste requires further optimization, as there are still challenges to overcome. The high processing costs and the challenges associated with scaling up the processes involved in the treatment of agro-industrial waste remain important obstacles.[18] Furthermore, the bioactive compounds obtained from this waste often have limitations related to stability, bioaccessibility, and bioavailability, depending on their specific application.[18] Ensuring compliance to regulatory frameworks in the intended application areas is essential, particularly in highly regulated sectors like the pharmaceutical industry, where compliance can be especially challenging.

Recent advances in biotechnology, nanotechnology, and circular economy models hold promise for enhancing the upcycling of by-products, thereby improving process efficiency and expanding the range of applications. Notably, nanotechnology techniques such as microencapsulation and nanoencapsulation have been employed to address previously mentioned issues, such as stability, solubility, and bioavailability of bioactive compounds, thereby enhancing these properties and expanding its applications.[18]

In conclusion, the chemical sciences play a crucial role in the valorisation of agro-industrial waste, allowing the extraction of bioactive compounds with potential applications in various industries, namely nutraceuticals, pharmaceuticals and cosmetics, contributing to human health and well-being. Furthermore, the application of chemical sciences facilitates the transformation of agro-industrial waste into biomaterials, offering sustainable alternatives to other materials which are harmful to the environment. The upcycling of these by-products reduces environmental burden, encourages more sustainable consumption practices and contributes to a zero-waste policy as well as the Sustainable Development Goals, namely those related with the natural resources shortage, climate change and responsible consumption. Despite these advantages, continuous research, technological innovation, and policy support in chemical sciences are important for progressing sustainable waste management and maximizing the effectiveness of upcycling initiatives.

Statement on use of AI

AI was used in the preparation of this essay to improve the language and readability. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the essay.

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Finalist

Fuelling the future: turning plastic trash into treasure

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Introduction: the plastic paradox

In 1907, when Leo Baekeland invented Bakelite, the world's first fully synthetic plastic, his revolutionary achievement promised endless possibilities.[1] Yet standing today at the edge of an endless landfill, gazing upon mountains of shimmering plastic waste, Baekeland's legacy feels hauntingly ironic: designed to last forever, plastic quickly becomes unwanted, disposable, and forgotten. Celebrated for its versatility and durability, plastic has now become infamous for its environmental harm. Each year, over 450 million tonnes of plastic are produced worldwide, yet less than 10% is recycled effectively.[2] The remaining majority is incinerated, landfilled, or worse, exported to other countries, where it often pollutes communities thousands of miles away, ending up burnt openly or dumped into oceans.[2] In the face of this unsettling truth, an urgent question arises: What immediate solution do we have to mitigate this environmental crisis while we wait for recycling infrastructure and technology to catch up?

Imagine if this environmental villain could be redeemed, if today's plastic waste could become tomorrow's energy. This isn't wishful thinking; it's a chemistry-driven reality, a transformative idea poised to rewrite our relationship with waste forever.

The challenge: the broken promise of plastic recycling

The very properties of durability and versatility that make plastics attractive have tragically become our downfall. Plastics do not biodegrade; instead, they fragment into microscopic pieces that infiltrate ecosystems, poison wildlife, make their way into the food chain and eventually enter human bodies. This gradual breakdown can release over 10,000 harmful additives, stabilisers, and absorbed environmental toxins, contaminating water, soil, and air, and endangering public health.[3,4]

Traditional recycling methods such as incineration, mechanical recycling, and traditional pyrolysis, each come with significant drawbacks. For example, incineration, although capable of energy recovery, emits large amounts of greenhouse gases and toxic pollutants, intensifying climate change and air contamination.[5] Whereas conventional pyrolysis remains economically challenging due to high energy inputs, inconsistent product quality from mixed plastics, and uncertainty in market valuation of pyrolysis oils, significantly limiting its broader adoption.[6,7] Mechanical recycling, widely promoted as a sustainable solution, struggles with contamination and the complexity of different polymer types, resulting in rejection of waste at recycling centres.[8–10] Collectively, these shortcomings lead to disappointingly low actual recycling rates worldwide.[11]

Yet, misleading narratives persist. Governments and corporations frequently mask this uncomfortable reality with carefully chosen language that gives the illusion of effective recycling. For instance, Somerset local council proudly claims that "100% of collected plastic waste stayed in the UK for recycling," conveniently not stating whether this waste was actually recycled.[12] Similarly, the UK government states that "64.8% of packaging waste was recycled," yet packaging waste accounts for less than half of the total plastic waste produced annually (40%), leaving the true scale of the plastic waste crisis understated .[13,14]

Clearly, conventional solutions are falling short. There is an urgent need for innovative, practical, and immediate alternatives; solutions that can bridge the gap between today's plastic crisis and tomorrow's circular economy.

The hero: hydrothermal liquefaction

What seems like magic is actually an elegant interplay of chemistry, thermodynamics, and reaction engineering. Enter Hydrothermal liquefaction (HTL): a process traditionally explored for biomass valorisation, has emerged as a promising method for converting unrecycled plastic waste into high-value synthetic crude oil, providing a practical pathway for waste valorisation and resource recovery.[15,16]

At its core, HTL achieves geological petroleum formation processes that takes millions of years, in mere hours. The fundamental chemistry involves subjecting plastic waste feedstocks to elevated temperatures (typically 280–450°C) and pressures (7–30 MPa) in an aqueous medium under oxygen-free conditions.[17] Under these hydrothermal conditions, water transitions into either a subcritical or supercritical state, profoundly altering its physical and chemical properties. Therefore, it no longer merely acts as a solvent but simultaneously takes on the roles of catalyst and reagent. These conditions shift reaction pathways towards radical-driven mechanisms. In either state, water exhibits significantly lower dielectric constants compared to standard conditions, enhancing its solvation power towards nonpolar organic compounds and therefore facilitating effective polymer breakdown.[17] The HTL process is illustrated schematically in **Figure 1**, highlighting its key stages and multiphase product outputs.

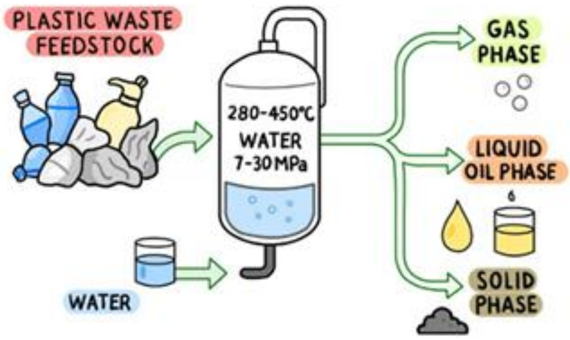

Figure 1 Simplified schematic of the hydrothermal liquefaction (HTL) process

Consequently, the resulting hydrocarbon products are distributed across distinct phases. The solid phase contains predominantly unreacted feedstock, larger hydrocarbons (C21+), insoluble polymeric residues (char), and inorganic impurities.[18,19] The most valuable liquid oil phase emerges from organic solvent washing and subsequent extraction, containing shorter hydrocarbon chains (C5-C21) that possess heating values often exceeding 40 MJ/kg, directly comparable to petroleum-derived fuels such as gasoline, diesel, and conventional crude oil.[18,19] Lastly, the shortest hydrocarbons (C1-C4), along with carbon dioxide and hydrogen, are collected within the gas phase.[18–20]

The strategic use of water grants several process benefits over traditional plastic-to-fuel technologies. Unlike pyrolysis, which requires energy-intensive drying of feedstock prior to treatment, HTL readily accepts wet feedstocks without preliminary drying. Moreover, due to the unique reactivity of sub- or supercritical water, HTL reaction conditions tend to be milder and more controlled compared to pyrolysis, which typically requires significantly higher temperatures and energy inputs. HTL also achieves higher liquid yields, frequently exceeding 80% by weight, with minimal char and gas byproducts, significantly enhancing its commercial appeal.[16]

However, the primary economic barrier in traditional HTL lies in maintaining the high operational pressures required for supercritical conditions.[16] Maintaining these demanding conditions (supercritical water at pressures >22 MPa) necessitates substantial energy inputs, high-pressure equipment, and associated economic challenges.[16]

Recent innovations, notably low-pressure hydrothermal liquefaction (LP-HTL), directly address these economic barriers by operating at significantly lower pressures (~1.55 MPa) using subcritical water. Research conducted by Jin et al. demonstrated that LP-HTL at these lower pressures maintains liquid fuel yields approaching 90%, producing high-quality synthetic crude oils analogous in composition and calorific value to those obtained at supercritical conditions, as temperature is the critical parameter that directly affects the product yield.[18,19] This innovative approach demonstrates remarkable process intensification: energy requirements reduce by up to 80%, and equipment capital costs decrease by approximately 90%, dramatically enhancing feasibility and scalability.[18,19]

The feasibility factor: can it work at scale?

This is not just a mere laboratory fantasy either. Companies like Mura Technology, in collaboration with Licella's catalytic hydrothermal reactor (Cat-HTR™), are currently constructing an industrial-scale facility in Teesside, UK. As of February 2025, this plant is in the commissioning phase, with plans to expand rapidly thereafter.[21–23] This plant will serve as a blueprint for a global rollout aiming to develop up to one million tonnes of plastic waste processing capacity worldwide by 2025, equivalent to nearly half the plastic packaging waste produced annually in the UK alone.[22] This facility will supply synthetic crude oil feedstocks directly to major chemical producers, including Dow Chemical, validating both the economic and environmental feasibility of HTL technologies.[24] Preliminary analyses indicate a reduction of approximately 1.5 tonnes of CO_2 emissions per tonne of plastic processed, compared to conventional waste incineration methods.[22]

While LP-HTL specifically remains at the lab and pilot-study stage, preliminary studies, and feasibility analyses, such as my own group's recent university design project, indicate its strong potential as a short-term stop-gap solution. Our comprehensive analysis, considering reactor design, economics, lifecycle impact, and scalability, underscored LP-HTL's promise while highlighting critical next steps: pilot-scale validation, robust impurity management, and comprehensive CFD simulations [M. Pekgoz *et al.,* unpublished report, 2025].

Navigating the challenges ahead

Nevertheless, significant hurdles must be overcome. Without effective separation or neutralisation, halogenated plastics (e.g. PVC) introduce severe corrosion concerns due to hydrochloric acid (HCl) formation, necessitating expensive corrosion-resistant equipment like stainless steel.[25] Furthermore, separating complex HTL product mixtures demands sophisticated downstream processes, increasing operational complexity and cost.[26,27] Precise control of process parameters, including temperature, pressure, and residence time, is essential to ensure consistent product quality and yield as well as economic viability.[28]

To overcome these barriers, future research should focus on detailed pilot-scale studies, optimising reactor designs via CFD modelling, develop robust impurity-handling strategies, and energy integration to enhance overall sustainability. Additionally, careful economic and environmental assessments should continually accompany technological developments to ensure LP-HTL remains genuinely advantageous over conventional waste management practices.[29]

A future fuelled by waste

For over a century, plastic has symbolised both human innovation and environmental tragedy. But perhaps its next chapter will be different. Perhaps the very material we once feared would outlive us all will, instead, fuel our future. The plastic that today symbolises pollution could one day symbolise hope and sustainability. Technologies like Low-Pressure Hydrothermal Liquefaction (LP-HTL) represent tangible, scalable interim solutions that transform a daunting environmental burden into valuable resources, buying precious time while permanent, circular recycling solutions mature. However, technological innovations like LP-HTL must be accompanied by wider societal shifts, reducing plastic consumption, improving waste segregation, and promoting a culture of sustainability.

The challenge is immense, but so is the opportunity. The question isn't whether we can turn plastic waste into fuel; it's whether we do. Rather than letting plastic waste accumulate for centuries, we hold the power to turn our weakness into strength. Truly the alchemist's dream, except this isn't gold from lead: it's fuel from waste.

Statement on use of AI

AI was used only to proofread and correct minor spelling or grammatical errors. All content, analysis, and conclusions are the author's original work.

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Finalist

Transforming waste into advanced materials: a sustainable chemical science approach

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Introduction

Global warming and climate change result from GHG effects caused by carbon dioxide, nitrous oxide, methane and hydrofluorocarbon gases, etc. Despite a brief decline in global GHG emissions brought on by COVID-19, the most recent Emissions Gap Report (EGR) from the United Nations Environment Programme (UNEP) showed a robust recovery in 2021.[1] Furthermore, in 2024, the UNEP report highlighted that food waste contributes to 8–10% of global GHG emissions, underscoring its significant environmental impact.[2] Unlike other types of food waste, bio-waste decomposes and releases methane, a GHG twenty times more powerful than carbon dioxide in terms of climate change effects.[3] As we progress toward a more sustainable future, the chemical sciences will continue to play a pivotal role in turning bio-waste into valuable resources. While bio-waste is commonly burned for energy or composted, these methods often don't fully capitalise on its potential as a raw material for advanced materials.

In recent years, waste materials, particularly bio-wastes, have emerged as the most intriguing carbon sources for synthesising carbon quantum dots (CDs) materials.[4] CDs are an emerging class of materials with a diameter of less than 10 nm.[4] CDs have a spherical shape, and their core can be crystalline, semi-crystalline, or amorphous in nature. CDs generally contain numerous organic functional groups, including carboxyl, amino, hydroxyl and carbonyl groups on their surface.[4] It can contribute to their chemical flexibility, excellent water solubility, large surface area, negligible cytotoxicity, optical tunable properties, and superior resistance to photo-bleaching that enhance CD's optical and physicochemical characteristics.[5] Hence, CDs are suitable for various biomedical and engineering applications.[5] Importantly, producing CDs from bio-waste ensures eco-friendly synthesis, easy access to the carbon source, low-cost sustainability and promising scalability.

Impact and implementation

CDs are generally synthesised from inexpensive carbohydrate sources like glucose, fructose, and sucrose.[5] Carbohydrate-rich bio-waste, such as banana peels, can be strategically utilised as a sustainable precursor for CDs to reduce GHG emissions. Globally, banana peel waste is among the most abundant bio-waste, comprising 35-40% of the fruit's weight and rich in simple sugars (~60%).[6] Recycling discarded peels for CDs synthesis provides a cost-effective carbon source and helps to mitigate GHG emissions. Recently, CDs have been sustainably synthesised from banana peel waste using mild oxidising agents at room temperature.[6] Green Analytical Chemistry enables CD purification by minimising the use of toxic chemical reagents. Similarly, researchers are exploring other bio-wastes, such as fruit peels and vegetable waste, to produce CDs via top-down and bottom-up methods.[4] From a sustainability perspective, selecting bio-waste as a starting material is crucial.

The chemical properties, structure, and surface characteristics of CDs can be precisely tailored for specific technological applications using a range of chemical science tools. These include applied chemistry, material chemistry, nanochemistry, analytical chemistry, surface chemistry, photochemistry, and physical chemistry, each contributing to the optimisation of CDs for enhanced functionality and performance (**Figure 1**). For example, CDs derived from bio-waste (e.g., banana peel) exhibit broad emission spectra, covering the entire UV-visible range (blue to red), producing pure white light that closely matches white-light coordinates (a scientific metric used for white light quality estimation).[6] Additionally, CDs and CD-NaCl crystals demonstrate lasing phenomena.[6] The NaCl matrix embedding the CDs acts as a resonant cavity, supporting Whispering-Gallery and Fabry-Perot modes that enable efficient lasing emission.[6,7] This outcome highlights non-toxic, metal-free CDs as promising candidates for white light generation and cost-effective lasing materials.[6,7]

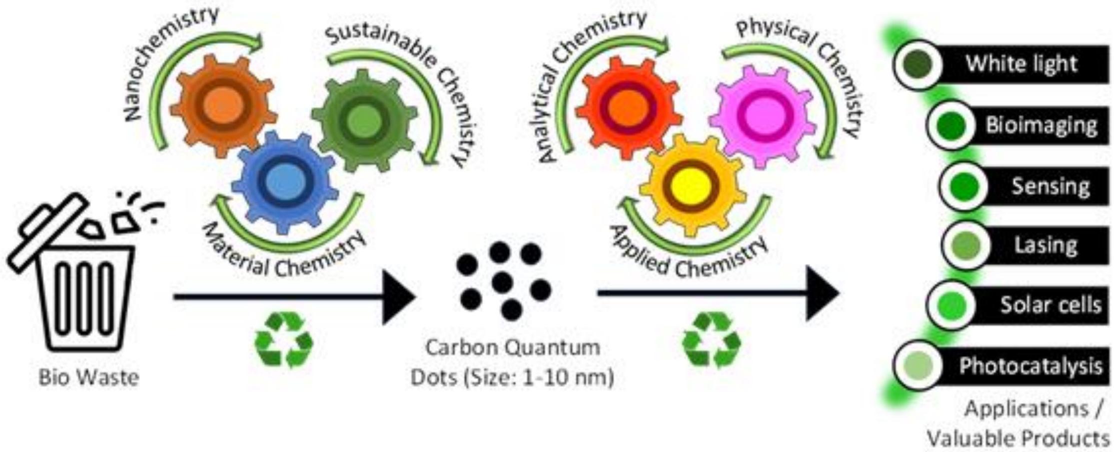

Figure 1 Sustainable transformation of bio-waste into various applications powered by chemical science

CDs generally show excitation wavelength-dependent fluorescence in the visible wavelength and exhibit poor quantum yield.[6] Consequently, CDs have very few biological applications because of their short wavelength emission and heterogeneity. Therefore, producing pure CDs with a high fluorescence quantum yield, longer wavelength range fluorescence, and excitation wavelength-independent fluorescence is extremely relevant to make bioimaging applications.[8] Importantly, the facile Synthetic Chemistry knowledge could help us to obtain pure excitation wavelength-independent CDs without further post-purification methods like column chromatography and dialysis, etc.[8] For example, excitation wavelength-independent green and red emissive CDs derived from banana peel waste have been demonstrated for bioimaging applications with negligible cytotoxicity.[8,13] Next-generation applications of CD emphasise on biological and biomedical applications such as drug/gene delivery, biosensing, photothermal therapy, and organelle bioimaging. Importantly, the in-situ method ensures analytical greenness and resource efficiency as per the Analytical GREEnness calculator.[9] To fully realise the potential of CDs from bio-waste, it is essential to combine green synthesis with digital technologies. AI, machine learning, and digital twins can accelerate the design, optimisation, and scale-up of these CDs materials. For instance, AI-driven predictive models can determine optimal synthesis parameters based on waste composition, thereby reducing energy consumption and chemical waste.

Moreover, CDs also offer a promising, affordable solution for water treatment as adsorbents with high adsorption capacity. These are also extensively used for fluorescence sensing of heavy metals (e.g., mercury, cadmium, lead) towards water quality testing.[10] Additionally, due to their excellent light-harvesting and conducting properties, CDs are implemented in LEDs, solar cells, and various optoelectronic applications.[11] CDs are also emerging as green alternatives to metal-based catalysts, with potential in photocatalysis, enzyme mimicry, and photodegradation.[12] These advanced materials contribute to the UN's SDGs Goal 6 (Clean Water and Sanitation) and Goal 12 (Responsible Consumption and Production) by enhancing water treatment efficiency, detecting pollutants, and promoting resource recovery from waste. More emphasis should be implemented on addressing challenges such as low fluorescence quantum yields of CDs and gaining a deeper understanding of their fluorescence origins.[13] Moreover, it is well proven that these sustainable CDs derived from nature (bio-waste) can demonstrate a wide range of potential applications. As rightly said by the eminent Indian physicist C. V. Raman, *"Ask the right questions, and nature will open the doors to her secrets."*

Digital chemistry and the twin transition

"Twin transition" goal[14] refers to the combined shift toward sustainability and digitalisation, where digital technologies like AI, digital twins, and machine learning accelerate green innovation across industries. "Twin Transition" is the synergy of "Digital Twin"[15] and "Sustainability" that enhances efficiency and supports green innovation, which is essential for long-term sustainability (**Figure 2**).

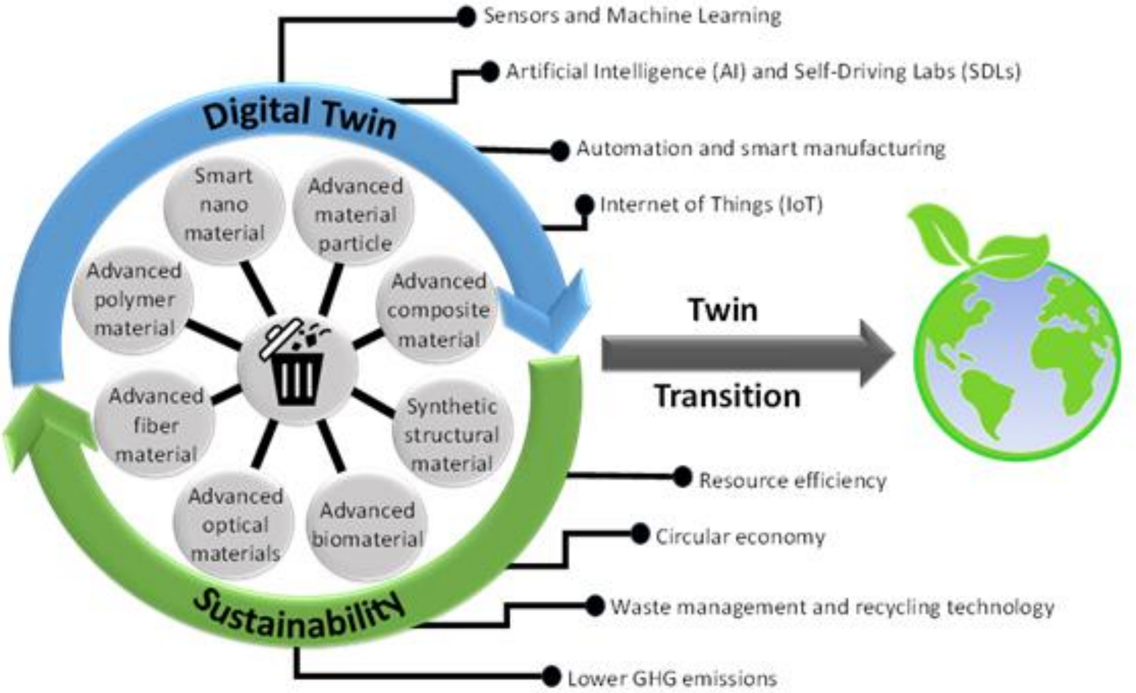

Figure 2 Digital Twin and sustainability reinforce each other to accelerate progress toward a greener future

Digital Twins replicate physical systems using real-time data from sensors, AI, SDLs, Internet of Things, and machine learning, where computational chemistry and chemometrics enhance their accuracy.[16,17] Consequently, Digital Twin plays a key role in sustainability by optimising energy conservation, reducing carbon footprints, and improving waste management. It can be adopted in smart cities, renewable energy, and green manufacturing on a large-scale basis to create a more sustainable and greener future. This transformation marks a paradigm shift where waste is no longer an end product but a valuable feedstock in next-generation material design through sustainability.

Conclusions and outlook

Chemical science plays a vital role in unlocking the potential of bio-waste, transforming it into valuable products and applications through sustainable practices. Recycling and upcycling bio-waste can address global GHG challenges, resource scarcity and promote a circular economy. However, the major challenges are high costs for bio-waste conversion, lack of scalable technologies, and inadequate infrastructure. Most research and studies have been performed in lab settings, and large-scale green synthesis of materials requires further research. Beyond bio-waste, Sustainable Chemistry offers solutions for transforming various forms of industrial, municipal, agricultural, and electronic waste into advanced functional materials (Fig. 2). Achieving this vision requires not only scientific innovation but also public awareness, supportive policies, and collaboration across various disciplines. With the right ecosystem, *Chemical Science* can lead the transition to a truly circular and sustainable future.

Statement on use of AI

AI technologies were used to check the grammatical errors and readability of this essay. AI was neither used to produce any images in the essay nor used to analyse data, draw scientific conclusions or provide References which do not exist. After using this tool/service, the author reviewed and edited the essay as required and takes full responsibility for the publication.

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Finalist

Catalyst immobilization on biopolymers - nature's best support

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Catalysis plays a key role in chemistry and is one of the twelve principles of Green Chemistry,[1] enabling efficient chemical reactions to proceed under milder conditions. Homogeneous catalysts are highly effective due to their tuneable selectivity and high activity. However, the synthesis of homogeneous catalysts/enzymes is typically resource intensive and transition metals (from metal catalysts) must be separated from reaction mixtures via onerous purifications to avoid product contamination.[2]

The immobilization of catalysts is a major step to facilitate catalyst recycling,[3,4] avoid metal contamination, and realize the integration of catalysts within continuous flow chemistry (CFC) systems. CFC systems are an enabling technology and provides a more sustainable option than traditional batch chemistry.[5–11] However, even CFC processes are not always 'circular';[11] the process is still essentially linear when it comes to the immobilized catalyst used within the CFC system if the catalyst and support are not recovered and reused.

Thus, the immobilization of catalysts on biopolymers is becoming a strong candidate to fulfil this need as such supports are renewable and biodegradable, and their properties can be engineered to create supports with varying morphology and porosity.[12,13] In addition, they can be depolymerized, thus enabling recovery of the catalyst.[14]

Synthetic supports such as polystyrene resins, silica, and alumina have been widely used as catalyst supports,[15] but are produced from fossil-based feedstocks using energy-intensive processing, and generate non-biodegradable waste. In contrast, biopolymers -natural polymers derived from renewable sources, offer a practical solution that bridges performance with sustainability. Biopolymer-supported catalysts have already received much attention (mainly) in batch systems, owing to their non-toxicity, renewability, biodegradability, and easy modification.[16,17] The most widely explored biopolymers as supports for catalysts in both batch and CFC systems include alginates, cellulose, lignin, and chitosan.

Alginates, commonly obtained as the sodium salt of alginic acid, contain carboxylic groups in each of the monomeric units of the polymer (**Figure 1a**). They are available at low cost and are generally used as a stabilizer and thickener in food products. However, their potential use as solid catalyst support for enzymatic applications[18] and as an organocatalyst,[19] are promising. Alginate is extracted from seaweed, forming gel-like matrices that encapsulate both metal catalysts and enzymes, making it particularly valuable in aqueous-phase reactions. For example, alginates have been used as catalyst support to support metal catalysts used for reduction reactions,[20] and addition reactions (Figure 1a). [21,22]

Lignin, a by-product of the paper and bioethanol industries, offers robust metal-chelating properties, enhancing catalyst stability in biomass conversion and hydrogenation processes. Lignin offers diverse functional groups (FGs), including hydroxyl (-OH), methoxy (-OCH_3), and phenolic (-PhOH) groups, which contribute to its reactivity and potential as a biopolymer-based catalyst support (**Figure 1b**).[23] Lignin (and its derivatives) have been explored as catalyst support materials for several organic reactions such as the [3+ 2] cycloaddition reaction,[24] and the Suzuki-Miyaura coupling reaction,[25] along with others.[26] An example in which a lignin-supported catalyst is used for Suzuki-Miyaura reaction is shown in **Figure 1b**.

Cellulose is the most abundant natural polymer, sourced from agricultural waste or recycled paper, and useful in large-scale applications such as biomedical devices, electrode capacitive applications, and the emerging landscape of smart electronic devices.[27] It possesses excellent mechanical strength, thermal stability, and a hydroxyl-rich backbone suitable for chemical functionalization and metal coordination[3] (**Figure 1c**). The functionalization of cellulose can be achieved via oxidation, acid hydrolysis, homogenization, and micro fluidization methods, leading to functional cellulose with improved properties than the parent cellulose biopolymer.[28] Furthermore, cellulose can be fabricated into nanofibers, papers etc. Cellulose-based materials, particularly cellulose nanofibers, offer significant advantages for sustainable catalysis due to their water-insolubility, tuneable surface chemistry, and ease of recovery from reaction mixtures.[29] Their ability to support metal catalysts enables catalytic processes under environmentally benign, aqueous conditions.[28] Cellulose has been a support for a range of metal catalysts used to achieve hydrogenation,[3] reduction,[30] Suzuki,[31] Heck,[32] and Ullmann coupling chemistry.[33] An example of Cu-phosphorylated cellulose for azide-alkyne cycloaddition is shown in **Figure 1c**.

Chitosan is a versatile biopolymer derived from chitin, primarily sourced from the exoskeletons of crustaceans such as shrimp, crabs, and lobsters. Thus, chitosan production relies on seafood waste.[34] Chitosan can take different forms e.g., colloids, flakes, gel beads, fibres (including hollow fibres), or immobilized on inorganic supports (alumina, silica, or other metal oxides.[35] It can easily be modified physically and chemically.[36] Chitosan is also porous, relatively inert compared to other biopolymers, and stable to reaction conditions.[37–39] Due to its unique amine and hydroxyl functionalities, (Figure 1d), chitosan is a useful support material. Chitosan has been used to immobilize metal complexes, organocatalyst,[40,41] and enzyme[42] and have been used in various organic transformations such as the Aza-Henry reaction[40], anilines-to-azobenzenes coupling reaction[43] and esterification of aryl aldehydes.[44] For example, chitosan supported cinchonine organocatalysts was used for asymmetric aldol condensation[41] (Figure 1d).[45–47] Additionally, chitosan-MnO_2-Ir/nanoceria supported nanoparticles (NPs) and chitosan-Ru-IrO_2 NPs have been reported as photocatalysts for water splitting.[48]

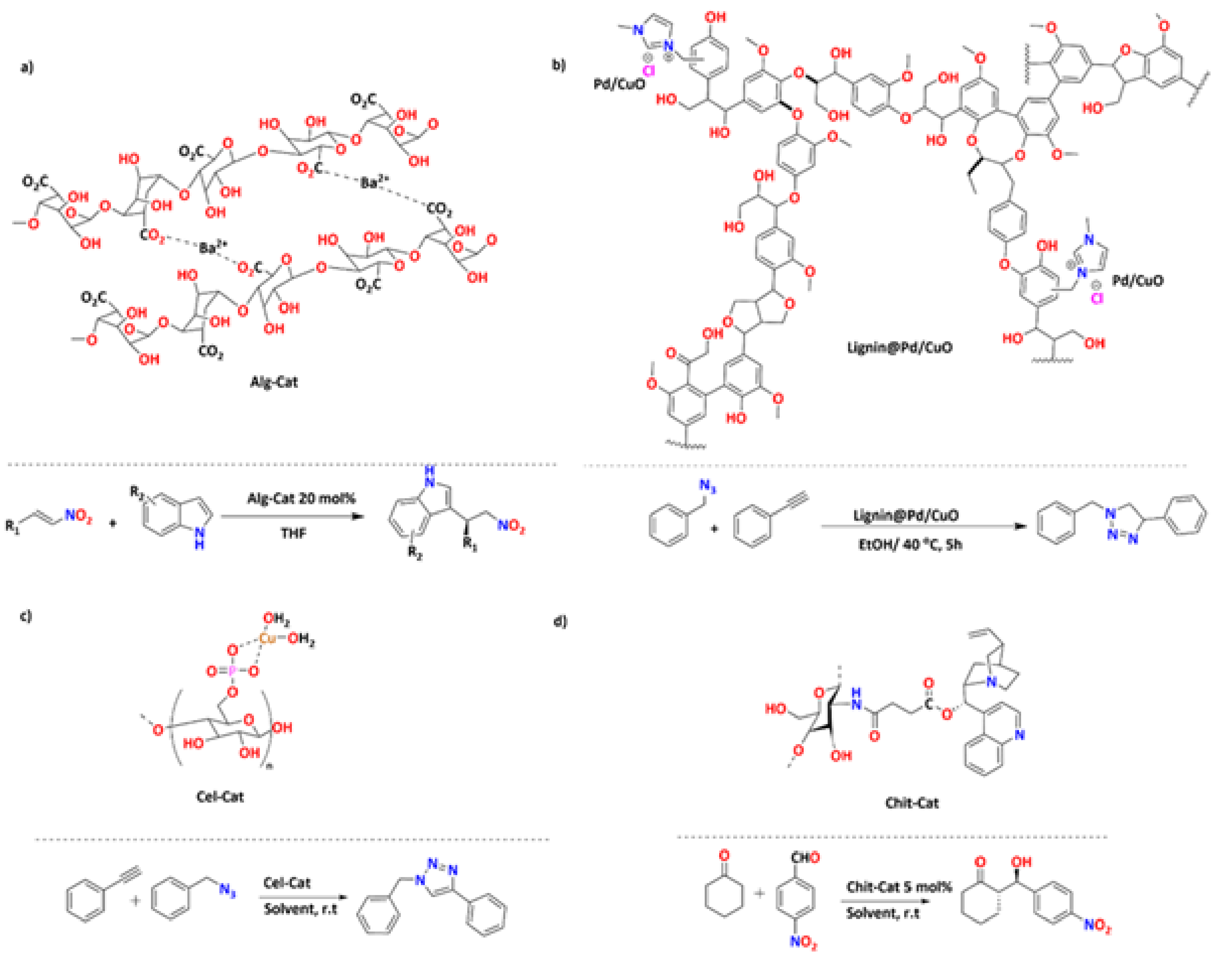

Figure 2 Selective biopolymers as a catalyst support for representative organic reactions: a) Alginate, b) Lignin, c) Cellulose and d) Chitosan.

Complex extraction techniques and environmental concerns over the production of alginate[49], lignin[50], and cellulose[51] sometimes make chitosan a "greener" choice. In addition, due to its complex structure and functional groups, lignin often faces difficulty in achieving site-specific functionalization and reproducible catalyst loading.

With increased demand for synthetic methods that are both efficient and sustainable, CFC is rapidly being implemented by industry (especially pharma industry)[9,10] as it is safer and greener, hosts lower reaction volumes, better control of reaction variables, better product selectivity, and generates vastly reduced quantities of waste.[5–8] Biopolymeric supported catalysts can be adapted to the CFC processes. In the only reported example, lignin was used to catalyse cross coupling and few click reactions, with good catalyst recovery and recyclability.[25]

Recently, it has been recognized that the use of biopolymer-based supports is gaining traction in establishing a circular economy in catalysis.[52] Synthetic polymer supports often become chemical waste with loss of the supported catalyst whereas catalysts immobilized on to biopolymers can be recovered, recycled and even possibly degraded environmentally, before being repurposed. For example, chitosan can be depolymerized using mild oxidation (e.g., H_2O_2)[53] or ultrasonication hydrolysis,[54,55] yielding valuable oligosaccharides which can be reused for several biological applications as they possess antithrombotic activity, antitumour activity[56] and antimicrobial activity.[57] The field of biopolymer-supported catalysis is still growing. While the number of proof-of-concept studies is growing, the challenge lies in translating laboratory success to industrial scalability. Key areas for future research include:

- Improving the mechanical properties of supports through novel processing methods,
- Exploring new synergistic combinations of biopolymers and inorganic materials for hybrid supports, to expand the knowledge base, and

Exploring new biopolymers as catalyst supports such as collagen, starch, pectin, and agar.

Statement on use of AI

The author declares that ChatGPT was used to improve grammar, language, and readability of the essay. The figures have been made using Chemdraw.

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Finalist

Water resource recovery: a sustainable approach for recovering nutrients, metals, clean water and energy from wastewater

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Water scarcity is a growing concern worldwide, threatening not only the environment but also humans (e.g., food security).[1] Population growth and climate change are key examples of increasing pressure on water availability.[1,2] Even though water is a main resource in itself, it is also a transport of other resources such as chemicals, energy and materials; valuable resources that are discharged to the environment. These extra resources are added to the water by processes like drinking water and wastewater coming from households, industry and buildings.[3] Usually, wastewater is considered an environmental hazard; however, it contains valuable resources that, if recovered, can contribute to sustainability.[3] Traditionally, wastewater has been treated for safe disposal, but recent advancements in chemical sciences have shifted the focus toward resource recovery. Innovative chemical processes now enable the extraction of nutrients, metals, organic matter, alginate and reclaimed water from wastewater and/or sludge,[4] a byproduct of wastewater treatment which contains phosphorus (P), nitrogen (N), and organic carbon. Also, the recuperation and production of energy at wastewater treatment plants (WWTPs) is possible through several advanced technologies that transform organic matter into bioenergy sources.[5] These processes are turning wastewater into a valuable resource rather than a waste product,[4] providing not only economic benefits but also environmental advantages, all with a focus on sustainability (**Figure 1**).[6]

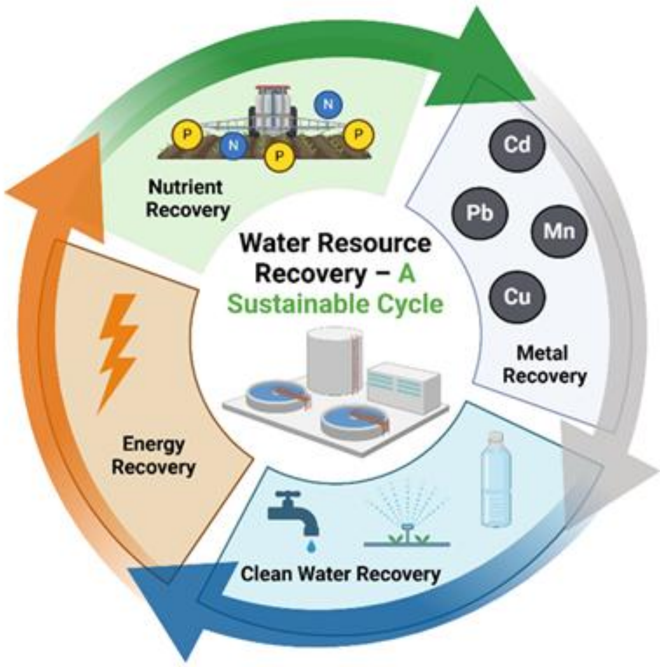

Figure 1 Schematic flowchart illustrating water resource recovery as a sustainable circular approach. Created in BioRender. Rapp-Wright, H. (2025) https://BioRender.com/13549v9

Nutrient recovery

Fertile soils are essential for sustainable crop production, with P and N being major nutrient inputs critical for agriculture,[7] limiting the food production industry. While N is not scarce, P is a finite resource, being declared as a critical raw material by the European Union (EU) in 2014.[8] Recovering these nutrients from wastewater would improve agricultural production and sustainability,[6] preventing eutrophication, saving energy and natural resources.[9] In wastewater, it has been estimated that over 80% of N and 50% of P content comes from urine.[10] Furthermore, approximately 22% of the global P demand could be covered by the content excreted by humans as faeces and urine,[11] making wastewater a valuable resource for nutrient recovery.

One of the main technologies for recovering P and N simultaneously from wastewater is chemical precipitation through the crystallisation of struvite ($MgNH_4PO_4$), a mineral that can be used as a slow-fertiliser (**Figure 2a**).[6,12] Even though low magnesium (Mg^{2+}) concentrations in wastewater are a limitation, they can be added to the treatment to form the desired ratio.[12] Furthermore, chemical reagents are the main cost of production, but there is research on low-cost magnesium sources, reporting an 18–81% reduction in operating cost.[12,13] Struvite has a P content comparable to phosphate rock and is commercially available across the EU. Of the 1,350 tons produced, up to 1,250 tons are estimated suitable for direct use as fertiliser or as a secondary raw material for fertiliser production,[14] reducing dependence on finite phosphate rock resources.

(a) $$H_nPO_4^{3-n} + Mg^{2+} + NH_4^+ + 6\,H_2O \rightarrow MgNH_4PO_4{\cdot}6H_2O + nH^+ \quad (n=1,2)$$

(b) $$2CH_2O + SO_4^{2-} \rightarrow H_2S + 2HCO^{3-}$$

$$H_2S + M^{2+} \rightarrow MS + 2H^+$$

where:
CH_2O is organic matter
M^{2+} is metal (e.g., Cd^{2+}, Mn^{2+}, Pb^{2+}, Cu^{2+}, etc.)

Figure 2 Equations for (a) crystallisation of struvite ($MgNH_4PO_4$) during the process of phosphorus and nitrate recovery; and (b) metal sulfide (MS) formation during the heavy metal recovery process, both from wastewater

Metal recovery

Industrial wastewater often contains valuable metals such as copper, gold, silver, and rare earth elements from mining, electronics, and manufacturing processes. When released, high concentrations of these metals can also be toxic to the environment.[15] A circular resource economy with systematic recycling could enhance the long-term availability of metals,[16] minimising the environmental impact.[15] Examples are gold and silver, which have successfully been recovered from wastewater by covalent organic frameworks (COFs), 98% and >95% respectively.[17,18]

There are several advanced chemical recovery methods such as precipitation by sodium hydroxide, an easy, low-cost method; however, this process has many limitations, including the production of unstable metal hydroxides. Ion exchange, electrolysis, and reverse osmosis are commonly used for recovery from heavy metals; however, these processes are costly, require additional treatment, and pose challenges related to secondary sludge disposal. Therefore, recent research has explored biosorption approaches using bio-based materials like algae and bacteria, offering eco-friendly solutions. Sulfate-reducing bacteria (SRB) is a widely preferred choice due to several advantages, including metal selectivity, low capital investment, high settling rates, and excellent thickening characteristics of the precipitates.[19] In this process, sulfate is initially reduced to sulfide by SRB, which then reacts with metals to form insoluble metal sulfide (MS) precipitates (Fig. 2b).[19] One limitation of this approach is the formation of insoluble MS precipitates, which contain nanoparticles of various MS. These nanoparticles are toxic to living organisms, posing an environmental risk if leached into ecosystems. Therefore, their complete recovery presents a significant challenge that needs to be addressed. However, some applications have been identified across various fields, such as the use of copper and iron sulfide nanoparticles for dye degradation[19,20] and removal of other heavy metals from wastewater,[19,21] respectively.

Overall, further research is needed to obtain metals in higher purity forms to expand their applicability across various fields. Additionally, the economic feasibility and viability of these systems may not be suitable for all WWTPs, highlighting the need for research focused on improving accessibility and scalability.[19] These processes not only reduce environmental contamination but also support sustainable resource management by providing an alternative source for critical metals.

Clean water recovery
Clean water recovery from wastewater is a potential solution to water scarcity and environmental pollution, making it an essential goal. There are three main applications for reclaimed wastewater: agricultural, industrial, and urban uses. Currently, it is used for irrigation, landscaping, cooling water for power plants, industry and toilet flushing.[22,23] However, agricultural applications, especially crop irrigation, are the most frequently used. Therefore, it is crucial to treat the water to a high standard for its safe reuse, to remove chemical, physical, physiological and biological contaminants.[23] Wastewater treatment combines physical, chemical and biological processes to remove these contaminants. There are some key chemical processes across the different treatments, such as disinfection and pathogen removal during tertiary (or advanced) treatment. Several technological advances in processes such as chlorination (Cl_2, NaOCl, ClO_2), UV radiation and ozonation (O_3) have minimised health and environmental risks, due to their high biocidal efficacy and degradation of trace organic chemicals (e.g., contaminants of emerging concern (CECs)).[24] However, these processes still have some limitations, such as the production of disinfection by-products or other chemical residuals, and their effectiveness being affected by particulate matter and dissolved compounds, among others.[25] Therefore, current research is increasingly focused on the sequential or combined application of these processes. However, studies in this area remain limited, highlighting the need for further investigation.[25]

The use of reclaimed water outside agriculture has also drawn attention to a more advanced circular economy. Potable water reuse has become a growing focus of recent research; however, several challenges remain, including inadequate regulations, difficulties in monitoring water quality, technological limitations, and uncertain environmental impacts, particularly risks associated with pollutants such as microplastics and CECs.[26] Further research is required to better understand the long-term environmental impacts, social acceptance, and economic feasibility of water reclamation projects.[26]

Energy recovery

Alternative energy sources are being investigated due to problems associated with fossil fuels. Approximately 400 trillion litres of wastewater are generated each year, and this amount is projected to rise by 50% by 2050.[27,28] Therefore, wastewater holds significant potential as a sustainable energy source.

There are several energy-extracting technologies such as anaerobic digestors, microbial fuel cells, salinity gradients or osmotic energy recovery processes that convert organic matter into energy sources.[27] Anaerobic digestion treatment is the most common one, and it produces biogas, a green and clean energy source.[29] The process consists of four stages: hydrolysis, acid-genesis, acetogenesis/dehydrogenation and methanogenesis. During these stages, bacteria break down complex organic matter (e.g., carbohydrates, proteins, fats, etc.) to the level of biogas consisting of methane (CH_4), carbon dioxide (CO_2) and other trace gases such as nitrogen (N_2) and oxygen (O_2). CH_4 is produced in higher quantities, and it is commonly used as a renewable fuel. However, some limitations affect the energy recovery like pH, temperature, and organic loading rate, among others. Nevertheless, energy recovered from meat and dairy industrial wastewater has already been utilised.[29] Furthermore, the sludge produced during the process is also used in agriculture after treatment, in particular in the Mediterranean region during summer periods, proving its efficacy as a soil organic amendment.[30] Current research is advancing these technologies by investigating additives to enhance gas production rates and designing cost-effective digesters adaptable to various WWTPs. These innovations contribute to greater environmental sustainability and overall improve energy recovery.

To conclude, advancements in chemical sciences are transforming wastewater treatment from a disposal-focused process to a resource recovery strategy. By extracting resources such as nutrients, metals, clean water and energy among others, these innovations contribute to environmental protection, resource conservation, and sustainable development. The use of wastewater as a source aligns directly with many United Nations Sustainable Development Goals (SDGs) such as 6 (Clean Water and Sanitation), 7 (Affordable and Clean Energy), 9 (Industry, Innovation, and Infrastructure), 12 (Responsible Consumption and Production), and 13 (Climate Action) by promoting waste reduction, resource efficiency, and climate mitigation. Many limitations have been identified; however, future research aims to address these challenges by exploring cost-effective, low-energy recovery methods and assessing their scalability to maximise impact. As chemical technologies evolve, wastewater will no longer be seen as waste, but as a crucial resource in the circular economy.

Statement on use of AI

No AI was used in the preparation of this essay, except for Grammarly for spell-checking.

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Finalist

Finalist

A systems approach to how chemical sciences can transform waste to valuable products

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With a growing global population, the world continues to see an increase in the amount of waste produced – over 2 billion tonnes of municipal solid waste (MSW) was produced globally in 2023 and this number is forecast to nearly double by 2050.[1] Likewise, electronic waste generation is increasing exponentially with an estimated 62 million tonnes of e-waste produced globally in 2022.[2] The management of waste, at such scale and complexity, is a colossal challenge and epitomizes a 'polycrisis', where interconnected systemic challenges compound and amplify one another: environmental degradation caused by waste generation contributes to climate change and biodiversity loss, economic inefficiencies drive resource depletion, and social inequities emerge through impacts of pollution and disproportionate waste burden on marginalized communities. This is also where conventional waste management strategies, such as landfilling and incineration fail, as these contribute to toxic atmospheric emissions and groundwater contamination.

In a world grappling with mounting waste,[3] dwindling resources and decarbonisation targets, the concept of waste-to-wealth is a powerful solution — a process of turning what was once discarded into a driver of socio-economic value and environmental sustainability. The current waste landscape encompasses diverse categories including MSW,[3] industrial waste including polymers,[4] agricultural residues,[5] e-waste,[6] and wastewater streams.[7] Each type of waste is characterised by unique physicochemical properties that can be systematically exploited to transform them into economically valuable products.[8] Such processes fundamentally challenge the traditional linear economy model characterized by 'take-make-dispose' patterns, which has resulted in resource depletion and environmental degradation. The approach of repurposing waste into valuable products reduces landfill burden, mitigates pollution, and fosters circular economies – advancing multiple Sustainable Development Goals (SDGs), including SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action).

At the core of unlocking this magical waste-to-wealth transformation is the chemical sciences, which through an integrated suite of approaches spanning multiple sub-disciplines, enables processes such as biomass valorisation, metal recovery from e-waste and upcycling of plastic waste. Analytical chemistry provides foundational capabilities for waste characterization through techniques such as chromatography, spectroscopy, and thermal analysis to determine composition and physicochemical properties essential for downstream processing decisions.[9,10] Armed with this knowledge, catalysts and adsorbents tailored to valorising specific waste streams, such as zeolites for plastic waste depolymerization[11] or metal-organic framework(MOF)-derived catalysts for biomass conversion,[12] can be synthesized. Subsequently, principles of physical and organic chemistry are used to elucidate reaction mechanisms and kinetics, enabling optimization of selectivity and product yield while minimizing unwanted side reactions in complex waste matrices. Such investigations are complemented by advances in computational chemistry, using tools such as density functional theory and molecular dynamic simulations, that improve the theoretical understanding of experimental observations.[13] These mechanistic insights help close the feedback loop informing the design of more efficient catalysts and processes. Process chemistry bridges laboratory insights to industrial implementation by developing methodologies for estimating mass and energy balances, conversion efficiencies, and life cycle impacts – often employing simulation tools and data-based approaches.[14] Thereby, the interconnectedness of different facets of the chemical sciences help achieve an improved holistic understanding of waste valorisation processes, resulting in significant improvements of the performance of such processes ('Chemical sciences sub-system' in **Figure 1**).

Over the years, different process routes have been developed for different kinds of waste. One such development is the concept of a biorefinery, which integrates multiple conversion pathways for converting renewable-derived feedstocks, such as bio-waste and biomass to valuable products that have conventionally been manufactured from a fossil fuel feedstock.[15] The thermochemical processes considered for biomass conversion include combustion, gasification (high-temperature process in an oxygen-limited environment), pyrolysis (high-temperature process in the absence of air) and solvent liquefaction (using moderate temperature and high pressure with a solvent medium).[16] Likewise, biochemical approaches using microorganisms and enzymatic systems to convert organic wastes into platform chemicals and biofuels have also emerged.[17] When it comes to e-waste, electrochemical processes such as electrowinning and electrorefining, help recover precious metals (gold, copper etc.) from the leachate solutions of acid-digested e-waste.[18] However, the role of the chemical sciences is not confined to waste processing alone. Working closely with engineers, the chemical sciences community is involved in the manufacture of products starting from virgin materials, which ultimately influences the type and quantity of wastes produced. In accordance with the 12 principles of green chemistry[19] and green engineering,[20] extensive emphasis is now placed on preventing waste, using renewable feedstock and designing products for a commercial 'afterlife'. Consequently, greater control can be exercised on downstream waste processing by adopting green principles for upstream product and process design ('Engineering design subsystem' in **Figure 1**).

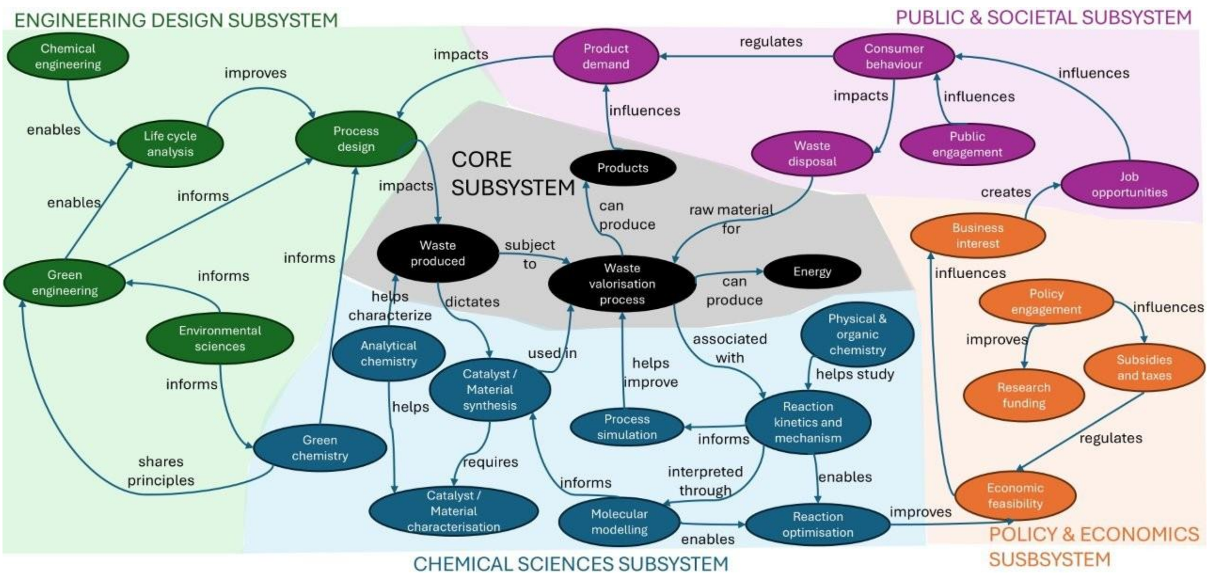

Figure 3 Systems-oriented Concept Map Extension (SOCME) for waste valorisation (core subsystem) showing the role of the chemical sciences subsystem alongside the engineering design, public & societal, and policy & economics subsystems
The SOCME was drawn by the author using Microsoft PowerPoint

Although the chemical sciences play an instrumental role in the above-described processes, realizing the full potential of waste-to-wealth requires more than just an understanding of the technological breakthroughs rendered possible by advancements through chemical sciences; it requires adopting a broader systems approach (**Figure 1**), mirroring the very essence of a circular economy, wherein the chemical sciences is a pivotal sub-system that interfaces with other disciplines (Engineering design subsystem) consumer behaviour (Public & societal subsystem) and government legislation (Policy & economics subsystem). The viability of waste valorisation is strongly influenced by consumer behaviour – appropriate waste segregation and disposal reduces the burden on waste sorting that simplify waste pre-processing. Likewise, responsible consumer behaviour at the time of purchasing products – for example, by prioritising products containing upcycled material – helps increase market demand and for waste valorisation processes to benefit from economies of scale. This is why chemical scientists engaging in more public engagement and outreach activities should be encouraged; although the proliferation of social media has eliminated barriers of access to information for the wider public, the credibility of information being consumed is often questionable. A more proactive involvement of the global chemical sciences community will help alleviate this issue. With access to internet rapidly improving in lower-income countries over the last decade, this opportunity can be harnessed to close the gap in 'controlled' waste disposal and management compared to higher-income countries (as defined in the United Nations Environment Programme (UNEP) report).[1]

Alongside public engagement, sharing of disciplinary expertise with policy makers is equally important ('Policy & economics subsystem' in **Figure 1**). As governments worldwide work towards net-zero targets in line with the Paris agreement, subsidies and taxes are powerful levers that legislative authorities can use to promote manufacture of products from various waste streams. Admittedly, the evolving global trade landscape and geopolitical scenarios will impact demand and supply of various products including fuels and energy; while this could have adverse socio-economic ramifications, this is also an opportunity for the chemical sciences community to liaise with policy makers to push for more robust infrastructure and manufacturing sites that use waste streams as the feedstock. Waste valorisation processes can reduce dependence on import of critical minerals and energy, both of which are vulnerable to economic and geopolitical shocks.[21] Thereby, national governments can be persuaded to increase research funding to improve the efficiency and economic viability of such waste valorisation processes. Going forward, breakthroughs in improving energy efficiency and process viability would increase interest among multinational chemical manufacturing businesses, but also lower the barrier to entry for small-scale and local manufacturing firms. Hence, from an industrial or business perspective, the economic appeal of processes that use waste streams as the feedstock can be modulated by both technological advancements as well as government initiatives incentivising waste valorisation, reinforcing the need to address this challenge from a broader systems perspective (**Figure 1**). The intricate influence of the different sub-systems depicted in Figure 1 also underscores the importance of strengthening systems thinking in chemistry education – an important project that has received backing from the International Organization for Chemical Sciences in Development (IOCD) and the International Union of Pure and Applied Chemistry (IUPAC).[22]

In conclusion, all sub-disciplines of the chemical sciences are crucial to the design of processes that convert waste to valuable products. Importantly, these different sub-disciplines do not work in silos but work in unison to advance the understanding and performance of waste valorisation. Framing the global waste problem as a 'polycrisis' helps us appreciate the necessity to adopt a systems approach to address the challenge. As described in this essay, systems thinking is not merely underpinned by studying interconnections between different aspects of chemistry, but also by how the chemical sciences interfaces with other disciplines (engineering and environmental sciences) and broader societal sub-systems (public & societal, policy & economics). Embracing a systems approach will provide the best chance of unlocking the full potential of waste valorisation processes, making it an endeavour that the global chemical sciences community must continue to passionately champion for in the future.

Statement on use of AI

Claude AI was used in the preparation of this essay to improve readability and language of the work. Having subsequently reviewed and edited the writing as necessary, the author takes full responsibility for the content presented herein.

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Finalist

From waste to resource: one person's trash is another person's treasure

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It is well recognized that our modern society has a waste problem.[1] The current global resource-utilization paradigm encourages consumption, which requires continuous production and extraction of the earth's often finite resources. Following use-stages, minimal emphasis is placed on the destination of many resources or products at end-of-use or -life. The consequences of such a linear system (production-use-discard) are evident across the world as levels of plastics pollution mount, greenhouse gas (GHG) production rises (*e.g.*, CO_2, methane), and other related wastes accumulate. Society's ever-increasing desire to own "*things*" amplifies the challenges of a linear economy, driving resource depletion and waste accumulation. At the same time, the impacts of other, less glamorized forms of waste—such as food wastes—are becoming of greater significance, highlighting the broader inefficiencies in how we use materials. Beyond tackling consumerism, what if we were to harness the power of chemical and related sciences to transform our "*trash*" into "*treasure*", creating valuable products and feedstocks for plastics manufacture or other markets (**Figure 1**)? These circularization strategies offer the potential to decrease pressures on water, land-usage, and finite resources, reduce the quantity of waste(s) entering our natural environments, and also present the opportunity to create new industries and job opportunities for countries across the world.

Figure 4 Overview of how the chemical sciences can transform wastes (plastics, agricultural, CO_2) to new materials

The chemical sciences have a strong footing in plastics waste conversion. Though mechanical recycling is an undeniably useful tool to repurpose and recycle commodity plastics,[2] chemical recycling is emerging as a new route towards high value monomers for further plastics manufacturing, or to produce chemicals for alternative markets.[3] For example, poly(ethylene terephthalate) (PET) represents a large share of the plastics production market (6.2%; 25.7 Mt in 2023)[4] and can be found in single-use drinks bottles, textiles, and other packaging materials. Due to its chemical make-up, PET can be depolymerized *via* chemolytic processes (methanolysis, glycolysis, hydrolysis, aminolysis, etc.) into polymerizable monomers, such as bis(2-hydroxyethyl) terephthalate, mono(2-hydroxyethyl) terephthalate, and terephthalic acid for closed-loop recycling.[3] Alternatively, leveraging transition metal chemistry or catalysed pyrolysis can unlock new fine chemical production or carbon-based materials which can be further utilized in energy-related applications.[5] New approaches are continuously being developed to transform more recalcitrant plastics that lack the innately labile bonds in PET, such as hydroconversions of polyolefins into lubricants or fuels,[6] thus reducing the need for additional petroleum/fossil-fuel extraction. Additionally, scientists are working towards chemical-upcycling of waste plastics by introducing new functionalities to produce inherently degradable or circular plastics or by incorporating small functional changes to waste plastics to make them depolymerizable.[7] One such example of this upcycling-to-circular approach is by inserting esters into polyethylene *via* Baeyer-Villiger oxidation to render them amenable to solvolysis at end-of-life.[8] Building end-of-life fates into polymer/plastics design, rather than considering as an after-thought, is a key feature for the development of future plastics. In the interim, tackling the existing ever-increasing mountain of waste plastics *via* chemical transformation(s) is necessary to curb pollution and preserve our natural environments.

Tapping into non-plastics sectors can offer a selection of novel chemicals and materials for manufacturing. For example, food- or agricultural-wastes can offer-up a surprising array of useful building blocks that can be leveraged for new plastics synthesis. Efforts to efficiently chemically extract cellulose, lignin, chitosan, or other bio-based compounds can uncover pathways to new monomers, which in turn reduces the need for additional petroleum feedstocks. For instance, lignin-based polymers are becoming of increasing scientific interest, and new isocyanate-free chemistries have been applied to create materials with comparable properties to petroleum-derived plastics.[9] Alternatively, acid-catalysed acetalization of xylose into dimethyl glyoxylate xylose presents a route towards synthesis of performance polyamides with improved properties *vs* typical petrochemical polyamides.[10] While the diversity of naturally sourced wastes can pose challenges for high-throughput production, research has shown that sequential acid/base extraction produces reproducible material yields, providing a stable source of waste-based molecules for further materials or chemical manufacture.[11] Wastes that are less tangible in nature can also be leveraged as valuable materials for plastics synthesis. Chemists have been investigating CO_2 as a new, "renewable" carbon source for utilization in synthesis with the potential added advantage of GHG removal from the atmosphere.[12] For example, CO_2 has been used as the precursor to produce a wide variety of compounds that can be leveraged for plastics production, such as hydrocarbons (xylenes, benzene, *etc.*), alcohols, acids (formic acid, which serves as a carbon-neutral hydrogen storage and production source), esters, aldehydes and ketones, carbonates (reaction of sodium carbonate and CO_2 to form sodium bicarbonate) or as a monomer and solvent during synthesis.[13,14]

Transforming wastes into new materials or chemicals underpins our transition to a circular economy; however, the root of efficient waste circularization and/or valorisation sits with effective waste collection and management. It is imperative to develop the associated collection schemes for these emerging materials to prevent mismanagement at end-of-life. Yet, it is important for us as scientists and chemists to recognize that adapting existing waste collection schemes is no easy feat. The complexities in adjusting collection schemes are geographical, infrastructural, and often also socio-economical.[15] For instance, there are over >9000 waste collection schemes in the United States (U.S.), > 39 in the United Kingdom (U.K.), and similar or greater geo-disparities across Europe, Asia, and Africa.[15] Unifying such collection schemes into national, or similar, directives, would require significant efforts from law makers, policy stakeholders, and high costs to modify existing infrastructure. Moreover, if we examine the flow of waste from use to recycling, we find that most waste collection begins with the consumer. However, evaluating the likelihood that a given consumer will participate in sorting-based waste disposal (recycling) is complex and depends upon perspective, demographic characteristics, psychological factors, knowledge of waste systems, morals and attitudes, trust and community, and political opinion.[16] Thus, although transformation of wastes is one route to supporting establishing a circular economy, we as a society must ensure that these efforts are sufficiently supported by 1) the development of the required infrastructure through collaboration of policy-makers, technical specialists, and scientists, and 2) global alignment on the importance of waste recycling through education, marketing, and relevant media outlets.

Overall, while this discussion has captured a few examples of waste transformations into new chemicals, building blocks, and plastic materials, insights from the broader literature can be applied across sectors, including targeted waste transformations into pharmaceuticals, bio-oils and bio-fuels, and beyond. Interdisciplinary collaboration across policy, science, and education is key to scaling waste transformation from the laboratory to industry and society at large. By shifting our mindsets from "trash" to "treasure" and recognizing the inherent value of materials otherwise deemed pollutants and waste, we can re-circularize the world's materials and chemical economy – reducing our reliance on finite feedstocks and the environmental impact effects of consumption, plastics pollution, food waste, and GHG emissions.

Statement on use of AI

No AI was used in the preparation of this essay.

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Finalist

Advancement in catalysis for transformation of waste-to-value

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Introduction

Along with the advancement of society, the accumulative consumption of resources has been rapidly increasing in the last century.[1] Consequently, there is a considerable amount of demand for resources to produce commodities. However, the linear economy model we adopted inevitably stimulated the rise of disposed waste by the growing number of productions.[2] On the other hand, continuing to operate in this manner will exhaust our natural resources and possibly leave nothing for our future generation. To prevent this catastrophic event, it is imperative to adopt a sustainable economy model. Circular economy model is trying to promote the utilization of waste as alternative resources and reduce the reliance of virgin material.[3] Moreover, the model implicitly pushes for a more responsible and sustainable process where the waste itself needs to be processable afterward, thus all the resources can be utilized efficiently.

In the last three decades, a significant amount of effort has been made to push on our understanding in the transformation of anthropogenic waste. From oil refining to commodity manufacturing and its consumption, various types of unwanted byproducts are formed constantly. Finding new utility to these wastes can create a meaningful purpose of usage and potentially beneficial for the economy in the long run. Chemical science has been one of the important tools for our breakthrough in advancing the circular economy and sustainable process. The general strategy to achieve this purpose is either by converting the waste back to its original feedstock or into new products and adding its value to the market. Among the field of chemical science, catalysis plays a key role in these processes by promoting the necessary chemical reaction. In this essay, various examples of waste-to-value will be presented as an introduction for the reader to grasp the vast possibility and importance of chemical science, especially catalysis.

Waste-to-energy

The most direct use of waste from plastic and biomass, and probably the oldest way in humankind history is to produce energy by combustion.[4] However, it suffers from low efficiency in comparison to commercial fuel. Nonetheless, catalytic processes such as hydrotreatment have enabled us to upgrade these wastes into fuel for transportation, i.e. food industry waste such as cooking oil into sustainable aviation fuel (SAF), paper and bioethanol byproduct like lignin into bio-oil or SAF additive, plastic waste into gasoline via pyrolysis.[5] Several studies also provided proof-of-concept to mixing plastic with biomass waste for upgrading oil.[6] On the other hand, industrial and transportation emissions such as CO_2 have been regarded as attractive feedstock to hydrocarbon, methanol, diesel through process such as Fischer-Tropsch process, with recent improvement on electro- and photochemistry have enabled the CO_2 reduction using renewable energy.[7]

Besides direct analogue of hydrocarbon fuel, clean fuel such as H_2 can be produced from water through electrochemical processes.[8] While it is common to use clean water, it is highly possible and beneficial to utilize alternative water from households, agriculture, pharmacies, and industries wastewater.[9] H_2 also can be produced from the byproduct of oil refining such as H_2S, or soap industry and biomass waste such as glycerol.[10] Another example of interest is the production of direct electricity through the cooperative performance of microorganisms and using MXenes catalysts in a microbial fuel cell system.[11]

In addition to conversion into fuel, catalytic processes enable the transformation of waste into an energy carrier, in this context for H_2.[12] Ammonia (NH_3) is considered as an attractive energy carrier due to its high hydrogen content, energy density, and zero carbon emissions, with the technology for its logistic and transportation are ready. With electrocatalysis, waste such as industrial NO_x gas or nitrate contaminant can be converted into NH_3.[13] Alternatively, cycloalkanes that are produced from hydrotreating and hydrogenation of biomass-waste lignin or oxygen-containing plastic such as polycarbonate (PC) and poly (ethylene terephthalate) (PET) can be considered as liquid organic hydrogen carrier (LOHC).[14] These examples underscore the important role of catalysis science for advancing technologies for converting waste into energy efficiently.

Waste-to-chemicals

Besides converting it into fuel, one different approach to utilizing our waste is via its transformation into valuable chemicals. The simplest idea of such conversion is through recycling the waste back into its former feedstock form. Mechanical recycling of various plastics made from polystyrene (PS), polyethylene (PE), or polypropylene (PP) has been extensively studied to convert back the material into its raw granulate forms.[15] The form granulate is commonly used back as the material to form the package or similar product with or without additional virgin feedstock.

Another potential process is via chemical recycling such as solvent-based and thermochemical.[16] Unlike mechanical recycling, the chemical process can convert the plastic waste back into its monomer form and not just granulate form, providing more flexibility to the utilization afterward and better quality in general. Recently, methanolysis of PC plastic has been developed to recover the toxic bisphenol A (BPA) monomer.[17] Besides PC, BPA also exists inside epoxy resin, which is commonly used in industry such as wind turbines. However, recycling epoxy resin is non-trivial due to its possible toxic side products like the fume. Nevertheless, several groups have developed catalytic processes using green solvent and reductant to recover the BPA under mild conditions with no harmful byproducts.[18]

On the other hand, chemical process is not only able to convert plastic polymer back to the monomer but also promote the transformation of the waste into other valuable compounds which is known as chemical upcycling.[19] Several catalytic processes using homogeneous catalysts have successfully converted real polyoxymethylene (POM) waste into methanol, dialkoxymethane, or cyclic aminals.[20] These products can be used as fuel, solvents, or additives to herbicide respectively. Another example is for polyvinyl chloride (PVC), a common polymer used in piping. Common high-temperature process for plastic degradation can produce toxic Cl-containing compounds such as dioxins, Cl_2 gas, and highly corrosive HCl. Nevertheless, recent advances in catalytic process and technology have provided saver pathway to PVC degradation.[21] Ru/Al_2O_3 promotes the transfer of Cl in the polymer to the biomass-based THF solvent and producing organic chloride compounds. The residue also can be selectively converted into CH_4.

Apart from conversion into fuel, CO_2 can be converted directly into valuable chemicals such as ethylene, formic acid, or oxalic acid through thermal and electro processes.[7] In addition, CO_2 can be coupled with organic compounds and provide valuable chemicals through various coupling reactions such as carboxylation.[22] Moreover, electrocatalytic reactions of CO_2 with N_2, NO_X or nitrate can provide valuable products such as urea.[23]

Future prospect

While the advances in science of catalytic reaction for chemical recycling of waste seems like a promising path to pursue, there are several things that must be considered before proceeding to the next scale-up technology. Most study on the development of the catalyst, whether homogeneous or heterogeneous, focuses on clean polymer. While this approach eases the study to elucidate the activity, the real waste feedstock does not solely consist of one clean polymer. Besides consisting of mixture of various plastic sources, one plastic product also didn't only come from a simple one-type polymer compound. A plastic product has additive compounds such as filler, stabilizer, and retardant, which are often ignored in the study despite the importance of implication for continuing to the scale-up with real feedstock. However, recent studies have tried to develop the catalyst with real feedstock in mind to mitigate the material's pitfall to these additives or other existing compounds. One example is the polyolefin plastic with its existing organic additives.[24] While recently developed catalysis is efficient for hydrogenolysis and hydrocracking, the existing additive compromised the activity. With these inherent problems in mind, the researchers looked for alternative, which microwave-assisted catalytic pyrolysis with zeolite HY showed durability to organic additive compound on the plastic. These results showed that, for further development of the catalytic waste-to-value process, it is necessary to consider real feedstock with its possible additives and contaminants. Additionally, it is worth noting to consider engineering the process for advancing the catalytic chemical reaction.

Summary

Progress on catalytic processes plays a vital role in waste-to-value process. Recent decades have witnessed numerous studies on the development of catalytic material for conversion of biomass and plastic waste into valuable commodities like fuel and chemicals. Although promising, there are still gaps for improvement in implementation from laboratory to larger scale, namely assessment on the real feedstock. However, these studies underscore the potential in achieving circular economy by reusing our waste. In the future, simultaneous advancement in material and reaction engineering is necessary to establish commercial process for sustainable waste-to-value.

Statement on use of AI

No AI technologies were used in the preparation of this essay.

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Finalist

Reclaiming landfill waste: chemical pathways for sustainable valorisation of waste rubber and waste plastics

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Sustainability has become one of the most urgent global concerns, as environmental degradation, biodiversity loss, resource depletion, and climate change threatening the well-being of future generations. Addressing these challenges demands an interdisciplinary approach, where chemistry plays a pivotal role in devising sustainable solutions that align with the United Nations' 17 Sustainable Development Goals (SDGs).[1] It should be noted that the chemical sciences significantly contribute to sustainability, more particularly in waste management, green chemistry, and material valorisation.[2] In this regard, a major focus lies in transforming waste materials (especially landfill-bound rubber and plastics) into valuable resources through innovative sustainable processes.[3,4]

The escalating accumulation of waste plastics and end-of-life-tires (EoLTs) in landfills poses severe environmental and socio-economic challenges. Originally intended as controlled disposal sites, landfills have become unsustainable due to the persistence of non-biodegradable waste. The sheer volume of waste generated globally exacerbates environmental impacts, with millions of tons of plastic waste entering oceans annually, contributing to marine pollution and biodiversity loss. It is expected that by 2030, approximately 50 million metric tons (MT) EoLTs will be discarded annually, further straining landfill infrastructure. Similarly, in 2019, 460 MT of plastics were manufactured, of which approximately 353 MT (77%) were discarded, with nearly 70% ending up in unscientifically created landfills/dumpsites and/or engineered landfills.[5–7] The quantity of waste plastics in landfills is expected to reach 12,000 MT by 2050, exacerbating concerns related to leachate formation, microplastic pollution, and greenhouse gas emissions. Additionally, rapid infrastructure development has led to land scarcity, intensifying concerns over landfilling.[7] Non-biodegradable plastic and rubber waste significantly contribute to land and water pollution, while disposal through landfilling and incineration releases harmful emissions.[8] Waste rubber, primarily from tires, is difficult to recycle due to its complex composition and cross-linked structure, while plastics, including polyesters and polyolefins, are highly resistant to degradation and mechanical recycling. Plastics derived from petrochemical sources degrade at an extremely slow rate, leading to long-term pollution and microplastic contamination.[7,9,10] Addressing these challenges requires chemical science interventions to break down, repurpose, and/or reintegrate these materials into the economy, minimizing environmental impact and fostering sustainability. Innovative solutions to transform these wastes into valuable products align with circular economy principles and contribute to Sustainable Development Goals (SDGs).

Chemical recycling techniques offer promising solutions by decomposing plastics and rubber into fundamental components. Pyrolysis, a thermal decomposition process conducted in the absence of oxygen, converts polymer waste into useful liquid fuels, syngas, and char.[11] Similarly, hydrothermal liquefaction utilises high-temperature and high-pressure water to depolymerise plastics and rubber, producing valuable hydrocarbons.[12] Advanced catalytic methods further enhance these processes by improving yield and reducing energy consumption.[13] Enzyme-based degradation has also shown promise in breaking down polymers under mild conditions, facilitating monomer recovery for repolymerised into new materials.[14,15]

Rubber waste represents a significant sustainability challenge due to its vulcanised structure, which makes recycling difficult. Mechanical recycling techniques, such as grinding rubber into fine particles for use in asphalt and composites, have been widely adopted.[4–6,16] Chemical recycling offers more efficient valorisation pathways, including devulcanisation, which breaks sulfur cross-links to enable rubber reuse in new products.[7] Moreover, eco-friendly solvolysis methods dissolve rubber to recover valuable elastomers, providing an alternative to traditional energy-intensive processes.

The chemical recycling methods can be categorised into three main pathways:

- **Depolymerization and chemical recycling**: This method breaks polymers into their original monomers, which can be used to produce high-quality recycled plastics. Catalytic pyrolysis and solvolysis facilitate monomer recovery, allowing re-polymerisation into new materials. For example, polyethylene terephthalate (PET) can be depolymerized into terephthalic acid and ethylene glycol, enabling closed-loop recycling, while devulcanization regenerates raw rubber for industrial applications.

- **Thermochemical conversion**: Pyrolysis and gasification efficiently convert waste rubber and plastics into energy-dense fuels and value-added chemicals. Pyrolysis, conducted in an oxygen-free environment, produces bio-oil, char, and syngas for use in petrochemical industries. Gasification, a high-temperature process with controlled oxygen, generates syngas rich in hydrogen and carbon monoxide, essential precursors for synthetic fuels and chemicals.
- **Solvent-based and enzymatic degradation:** Recent advancements in green chemistry explore solvent-based recycling and enzymatic degradation. Ionic liquids and supercritical fluids enable selective dissolution and recovery of polymer components with minimal degradation. Engineered enzymes, such as PETase break down PET into monomers, offering an eco-friendly alternative to traditional recycling.

Incorporating waste-derived materials into construction applications provides sustainable pathway by reducing greenhouse gas emissions and promoting a circular economy. Rubber-modified concrete exhibits enhanced flexibility, thermal insulation, and durability, making it ideal for infrastructure projects in extreme environmental conditions. Similarly, plastic-derived aggregates and binders contribute to lightweight, high-performance building materials, reducing reliance on virgin resources. These applications exemplify how chemical sciences can convert waste into functional materials, supporting circular economy principles and minimising landfill dependency.

Beyond material valorisation, chemical sciences facilitate the development of biodegradable alternatives to conventional plastics.[14,15] Bioplastics, synthesized from renewable feedstocks such as polyhydroxyalkanoates (PHA) and polylactic acid (PLA), degrade more readily in natural environments compared to petroleum-based polymers. Research into bio-based elastomers will provide long-term solutions and sustainable alternatives to synthetic polymers, reducing reliance on fossil fuels while maintaining material performance.[15] Further developments in green chemistry focus on optimising solvents, catalysts, and processing methods to enhance efficiency and reduce environmental impact. Supercritical fluid technology, ionic liquids, and mechanochemical processes are being explored to improve plastic and rubber recycling while minimising hazardous byproducts and energy consumption, which would make sustainable waste processing more viable at an industrial scale. Despite the above-mentioned advancements, challenges remain in scaling up these technologies. Unfortunately, economic feasibility is a significant barrier as many advanced recycling methods require high initial investments. Despite technological improvements, energy efficiency remains another concern as some processes are still highly energy-intensive. A schematic representation of the chemical pathways and circular economy associated with waste plastics and rubber has been presented in **Figure 1**.

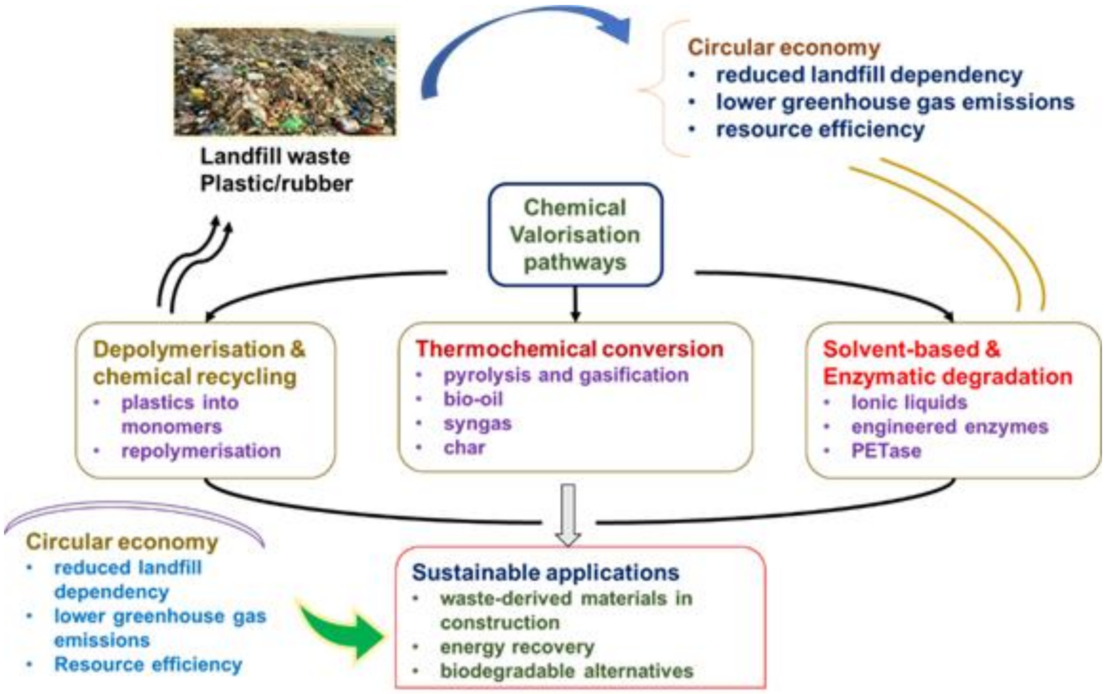

Figure 1 Circular economy associated with chemical valorisation pathways of waste plastics and rubber

Furthermore, policy frameworks are crucial in promoting circular economy practices at both local and global levels. In this regard, collaboration between scientists, policymakers, industries, and consumers is a must to accelerate the transition toward sustainable solutions.[3,17] Effective science communication and collaboration ensure that advancements move beyond laboratory and pilot-scale demonstrations to real-world applications by fostering interdisciplinary research and engaging society to drive behavioural changes. Addressing ethical considerations is equally important to ensure technological advancements benefit all segments of society equitably while avoiding environmental injustices. Measures such as extended producer responsibility (EPR) schemes can mandate producers to manage end-of-life products, while tax incentives for recycled material usage can enhance industry participation by offsetting costs. Also, stricter landfill regulations discourage waste accumulation while promoting chemical recycling and material valorisation. Standardising recycling processes across industries, though challenging at this stage, would further improve efficiency throughout supply chains, making waste management more effective on a global scale.

The critical environmental and socio-economic implications of sustainable waste valorisation are as follows:

- **Reduction of landfill waste and pollution:** The rubber and plastic waste stacking in the landfills should be diverted to chemical recycling and valorisation processes, which will help to mitigate environmental pollution and reduce risks of soil and water contamination from microplastics and hazardous leachates.
- **Energy recovery and resource efficiency:** The production of synthetic fuels by performing energy recovery would decrease reliance on fossil resources. Also, the recovery of raw materials from waste minimizes the demand for virgin polymers, lowering carbon footprints associated with traditional manufacturing.[5]
- **Economic and industrial benefits:** The waste-to-resource industries foster economic growth and promote sustainable manufacturing. Companies adopting chemical recycling technologies gain competitive advantages by reducing raw material costs and aligning with global sustainability initiatives.

Therefore, effective waste management policies should encourage the adoption of chemical valorisation technologies through incentives and regulations. At the same time, collaboration among industries, governments, and research institutions is essential for scaling up sustainable recycling. Future research should focus on optimising catalyst efficiency, reducing energy consumption, and developing biodegradable plastic alternatives. The sustainable valorisation of waste rubber and plastics through chemical sciences presents a promising pathway to mitigating landfill waste while enhancing resource efficiency and reducing environmental impact. Polymeric waste can be transformed into valuable products that drive the transition toward a circular economy by harnessing innovative chemical processes such as depolymerization, pyrolysis, enzymatic degradation, and devulcanization. It should be noted that achieving long-term sustainability will require continued research investments alongside supportive policies and industrial collaboration. By embracing these chemical pathways and addressing associated challenges, landfill waste can be effectively managed, contributing to a more sustainable future.

Statement on use of AI

AI or AI-assisted technologies were not used to prepare this essay, except for Grammarly for spell-checking purposes only.

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Finalist

A quantum stride in chemical science to simultaneously address plastic pollution and carbon neutrality for environmental sustainability

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Every year, humanity releases billions of tons of CO_2 into the atmosphere, driving global warming and pushing our planet toward an existential crisis. In 2024, it increased by 0.8% to record atmospheric CO_2 concentrations of 422.5 ppm.[1-3] For centuries, nature has been our ally in this fight, as plants captured CO_2 and converted it into life-sustaining glucose. But the scale of our emissions has far exceeded what nature can handle. On the other hand, every minute, the equivalent of a garbage truck's worth of plastic, 14 million tons annually, dumps into our oceans, making 80% of all marine debris at the bottom, destroying ecosystems, infiltrating the food chain, and poisoning marine life.[4] Unlike terrestrial ecosystems, where conservation efforts such as national parks and reserves help protect species, marine biodiversity lacks such dedicated safeguards. Many species may already be facing extinction due to marine pollution and warming waters, yet remain undocumented. By 2050, scientists have warned that there will be more plastic than fish in the sea if no action is taken.[5] Nature struggles to decompose this man-made avalanche as a single plastic bottle takes 450 years to break down, persisting as microplastics that now course through our blood, rain from the sky, and even lodge in Arctic ice.

Plastics, comprising 12% of global waste, are notoriously difficult to recycle due to contamination and degradation during conventional processes.[6] This results in most plastics being landfilled or incinerated, exacerbating pollution and resource depletion. At the same time, Industrial activities emit over 36 billion tons of CO_2 annually, with current carbon capture methods being energy-intensive and expensive. Without innovative approaches, this waste will remain a leading contributor to pollution and global warming. Acknowledging the threat is no longer enough, and we must act, act decisively. The question is no longer whether we can act but how quickly we can scale these solutions to secure a thriving planet for generations to come. We need faster, smarter, cheaper solutions, and that's where innovation steps in.

By capturing CO_2 at its source, that is, industrial chimneys, exhaust systems, and power plants, using it to degrade plastics and convert it into fuels and chemicals, we can turn these pervasive problems into a powerful opportunity. Here we explore the novel idea and chemistry of CO_2-assisted plastic degradation, focusing on next-generation catalysts designed to withstand extreme conditions, degrade plastic and convert CO_2 into valuable products, and pave the way for a sustainable future as shown in **Figure 1**. The solution lies in the development of advanced catalysts capable of tackling both problems simultaneously. Catalysts are materials that accelerate chemical reactions without being consumed, and are the cornerstone of many industrial processes. They can enable the efficient transformation of CO_2 into fuels and chemicals and degrade plastic into smaller, useful molecules under mild conditions. By coupling CO_2 utilisation with plastic degradation, catalysts can achieve dual functionality: capturing CO_2 at its source, like industrial chimneys, power plants, and exhaust systems, and using it to drive the breakdown of stubborn plastics into valuable products.

Traditional plastic-degrading catalysts like zeolites and solid acids, which feature Brønsted and Lewis acid sites at the molecular level, have long been used to weaken the strong polymeric bonds in plastics, lowering energy barriers and degrading them into smaller chains and, ultimately, into fuels or valuable chemicals.[7,8] These products are less harmful to the environment than conventional plastic disposal methods, such as incineration or landfilling. However, the efficiency of these catalysts is limited due to issues like low porosity, which hinders access to the active sites and reduces overall catalytic performance. CO_2, being a small molecule and a Lewis acid itself, offers an intriguing solution. By leveraging unique properties of CO_2, it can act as a co-reactant on catalysts designed to adsorb both CO_2 and plastic polymers. In this system, CO_2 molecules penetrate the polymer chains on the catalyst's active surface, promoting their degradation into smaller, more manageable fragments. Research focused on developing advanced catalysts that synergistically combine the adsorptive properties of CO_2 with enhanced catalytic activity will act as a dual-edged sword. These catalysts should possess high surface areas, optimized porosity, and tailored active sites, enabling the simultaneous adsorption of CO_2 and plastic chains in spatial proximity. The process results in efficient plastic degradation, addressing the limitations of traditional methods while offering a pathway to valorise both plastic waste and CO_2.

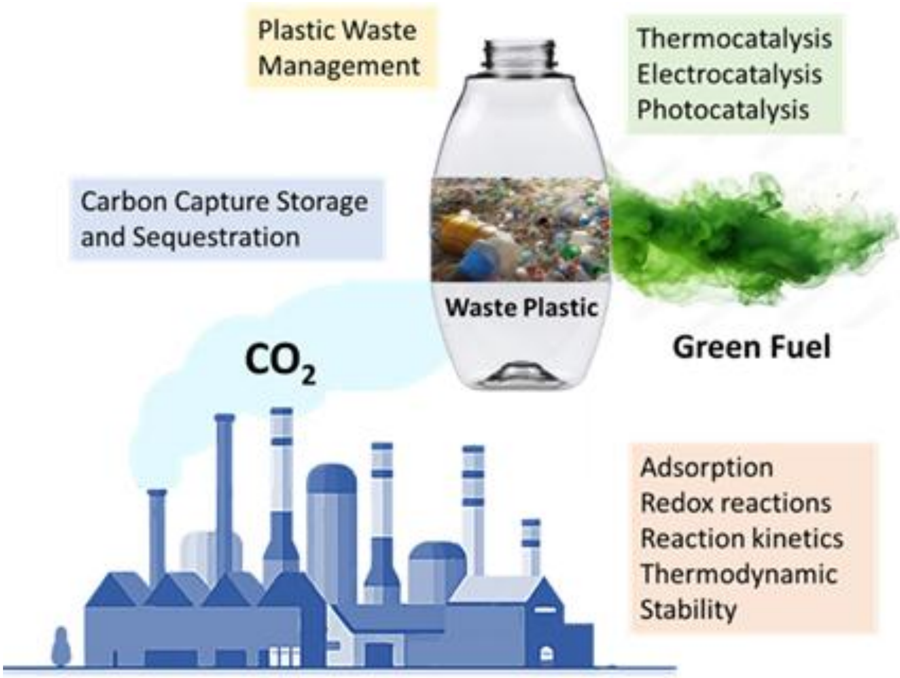

Figure 1 CO_2 assisted dual action catalysis for sustainable plastic degradation

Although designing such catalysts is not a trivial task, as it requires multitasking materials that can withstand extreme reaction conditions while exhibiting high selectivity, efficiency, and durability. To design an effective catalyst, understanding the molecular-level interactions between CO_2, plastics, and the catalytic surface is critical. The chemical principles required here are catalysis, adsorption, redox reactions, reaction kinetics, and thermodynamics. This is where sophisticated characterisation techniques play a pivotal role. The multidisciplinary nature of chemistry enhances these efforts, integrating materials science for catalyst design, engineering for process optimisation, and computational modelling for mechanistic understanding. Advances in spectroscopy, microscopy, computational modelling, and artificial intelligence allow researchers to probe catalytic processes in detail. The synergy between these fields ensures the development of catalysts that are not only selective and efficient but also scalable for industrial applications. This approach mitigates the environmental impact of plastics in addition to transforming waste into resources, contributing to a closed carbon economy and reducing reliance on fossil fuels. Integrating these processes into industrial systems can reduce reliance on fossil fuels, lower greenhouse gas emissions, and minimise environmental harm. However, the path to large-scale implementation is not without challenges. Scalability, cost, and long-term stability of these catalysts have to be addressed. Collaborative efforts between academia, industry, and policymakers will be essential to bridge the gap between laboratory research and real-world applications.

The potential impact of this research extends beyond just reducing pollution. Turning waste into useful materials can help us move toward a circular economy, where resources are reused rather than discarded. This would decrease our dependence on fossil fuels, lower carbon emissions, and also reduce the environmental damage caused by plastic waste. However, for these technologies to be implemented on a large scale, challenges such as cost, scalability, and long-term stability must be addressed. Collaboration between scientists, industries, and policymakers will be essential to bringing these solutions from the laboratory to the real world.

The battle against ozone layer depletion is a powerful reminder of what the chemical science community can achieve with global cooperation. In the 20th century, chlorofluorocarbons (CFCs) were identified as the primary pollutants behind the thinning of ozone layer.[9] Chemical science played an important role in understanding this phenomenon, elucidating the mechanisms by which CFCs released chlorine atoms that caused ozone destruction. With this knowledge, chemists developed safer alternatives to CFCs, such as hydrofluorocarbons and eventually hydrofluoroolefins, which have lower global warming potentials. The Montreal Protocol, signed in 1987, showcased the power of global commitment, successfully phasing out ozone-depleting substances and setting the stage for the gradual recovery of the ozone layer.[10] This triumph affirms the capacity of chemical science to not only identify problems but also devise effective solutions. Today, we stand at a similar crossroads. The Paris Agreement, adopted by 196 parties at COP21 (Conference of the Parties) in 2015 and force since 2016, is a legally binding treaty on climate change. It aims to keep global temperature rise well below 2°C, with efforts to limit it to 1.5°C.[12] Scientists warn that exceeding 1.5°C risks severe climate impacts. To stay within this limit, emissions must peak by 2025 and drop 43% by 2030.[11] This agreement unites all nations in the fight against climate change. We have done it before, so we can and must do it again.

These twin crises of climate change and plastic pollution demand urgent and effective solutions. Using the power of next-generation catalysts, sophisticated characterisation techniques, and advanced chemical science, we can turn these challenges into opportunities for a sustainable future. The question is whether we will deploy them at the speed and scale required or let carbon emissions and plastic's legacy also drown future generations in a sea of our own making. With the right investments in research, technology, collaboration, and sustainable goals, we can secure a thriving planet for generations to come.

Statement on use of AI

No AI was used in the articulation of the central and scientific idea of this essay. AI tools were used for readability, spelling and grammar corrections.

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Finalist

How legislative norms in decarbonization strategies shape the transition to sustainable aviation fuel; a comparative analysis of the United Kingdom and European Union

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The urgency of CO_2 emission reduction significantly gained recognition over the past decade; a development that is primarily rooted in the 2015 Paris Agreement that set various obligations to ensure that global warming would not exceed 1.5 degrees by 2050. For this reason, a significant reduction in CO_2 emissions from international aviation has shown to be crucial; if these emissions continue to increase the industry would be responsible for a quarter of the total amount of 'allowed' (according to the 1.5 degrees objective) CO_2 emissions by 2050.[1] Therefore, the Paris Agreement triggered an increasing dependence on sustainable alternatives such as 'sustainable aviation fuel'(SAF); a transition that has been facilitated by innovative production methods like waste valorisation. SAFs are fuels produced from sustainable sources of energy like recyclable feedstock,[2] consisting of waste materials of biological origin. Converting this material into usable fuel that can at least partially replace kerosene (through blending), is done via various chemical processes, emphasizing the role of the chemical industry in facilitating waste valorisation in the aircraft sector. When it comes to regulations aimed at legally shaping the process of SAF production and adoption, the European Union is leading the way globally; its 2023 "ReFuelEU Aviation" policy requires firms to gradually increase their supply of SAF to EU airlines, to achieve a minimum of 63% blending of SAF in aviation fuel by 2050,[2] but also mandates its uptake at EU airports.[3] The United Kingdom, which is no longer part of the European Union, managed to keep up with the SAF objectives of the EU but did not set legal obligations directly to airlines in the way the EU has done, whereby British airlines currently are not directly obliged to a minimum percentage of SAF at their airports; making the country's SAF uptake less stable. This highlights the importance of binding obligations for airlines themselves in assuring consistent growth in SAF uptake for the purpose of accelerating the process of decarbonizing the European aviation industry as a whole.

The academic debate on sustainability in international aviation has been widely centred on the role of sustainable aviation fuel in reducing the amount of CO_2 emissions the industry accounts for. Even though it accounts for a relatively small share of the total global emissions, around 2.6%,[4] the previously mentioned prediction that by 2050 the industry would be responsible for a too large share of the total CO_2 emissions 'allowed' under the emission limits set by the Paris Agreement, increased the urgency for the industry to reduce its reliance on the carbon-intensive fuel kerosene. The potential of sustainable aviation fuel, also referred to as SAF, as being the alternative to kerosene has gained significant recognition; the global aircraft organisation IATA considers SAF to be "the most promising strategy to reduce CO_2 emissions in the aviation sector".[2] It is a type of fuel derived from either renewable or recyclable feedstocks; the use of those feedstocks reduces CO_2 emissions by almost 80% throughout the fuel's life cycle.[2] This, among other things, results from the cultivation and harvesting stages of that type of (second-generation) feedstock that entail relatively low emissions.[5]

Since this non-fossil feedstock consists of waste products such as used cooking oils and animal fats,[6] SAF production is realised through 'waste valorisation', which refers to "the process of reusing, recycling or processing waste materials and transforming them into value-added products".[6] The previously mentioned waste materials facilitate the production of 'HEFA'. This is the term for a type of sustainable aviation fuel that is produced through 'hydrodeoxygenation'; a chemical technology that refers to "the removal of oxygen in the presence of hydrogen",[7] making the product convenient for blending it with fossil-based fuels like gasoline.[8] This possibility of blending has made the use of HEFA fuel relatively accessible for airlines, since it requires no total abandonment of the fossil-based fuel they already rely on. In addition, the price development of HEFA is the most favourable as it is expected that its price will fall below the price of fossil kerosene after 2030.[1]

The United Kingdom has shown to, despite the fact that it is no longer part of the European Union, not lag behind with regard to SAF-regulation. The country introduced the so-called 'Jet Zero Strategy', which points out measures and funding commitments aimed at fulfilling the ambition of zero CO_2 emissions resulting from air travel in 2050.[9] The Jet Zero Strategy includes several targets of SAF usage in the UK increasing over time, from 10% by 2030 to 50% by 2050.[10] As stated in the strategy this is facilitated, among other things, by establishing production plants that realise SAF supply on a national scale, with the objective of having five plants in the process of construction by 2025.[9] One of those production plants that is already in operation is the "Phillips 66 Limited Humber Refinery", that managed to utilize its already existing processing capabilities in such a way that they can produce SAF from waste oils.[9] The impact this refinery made is evident from the fact that the country's largest airline, British Airways, received its first supply of SAF from this specific refinery.[9] This demand coming from a 'high level' underscores the importance and potential of chemical processed waste oils (HEFA method) in particular, in providing stability in both SAF demand and supply within the UK. However, in contrast to the EU's Refuel Aviation initiative, 'Jet Zero' does not directly impose obligations mandated by law to airlines regarding SAF uptake; it primarily seeks to achieve its short-term objective of constructing production plants and long-term targets of SAF usage through subsidies and incentives intended to significantly stimulate SAF production and adoption. Thereby, the British government has laid the foundation for a stable SAF market but the absence of legally mandated SAF targets airlines explicitly have to commit to, puts the risk of relatively slower SAF adoption in comparison to airlines in EU countries, which is for example demonstrated by the fact that British airlines are not in the top three (that is dominated by airlines from Scandinavia) when it comes to the goal passenger airlines themselves set for SAF uptake by 2030.[11] The strict uptake percentages introduced in the RefuelEU initiative created more of a "level playing field",[12] with equal fuel costs between EU airlines, since the initiative gives these airlines no option to postpone their shift to SAF use.

As the country that sells the highest percentage of the total available seats for flights departing from airports on the European continent,[13] the United Kingdom plays a significant role in the European aviation market and the way and pace at which the decarbonisation of this market as a whole is progressing. Despite the developments in the British SAF market being relatively similar to those in the EU, they have been legally structured in different ways. This emphasizes the importance of bridging the gap between the United Kingdom and the European Union when it comes to providing a high degree of certainty for the aviation industry and investors through strict and clear legislation, thereby addressing the difference in speed at which airlines in both markets undergo a transition to SAF usage. After all, a clear visibility of airlines' participation in this transition, which have the shortest communication lines with passengers, will ultimately be decisive for a passenger's perception of SAF and the extent to which he or she is willing to accept the relatively higher costs the adoption of most of its variants entail for the time being.

Statement on use of AI

AI was used in the preparation of this essay to improve readability and language of the work.

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Finalist

Cow's manure reinvented: how chemical processes cause waste products and how to prevent this

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Agriculture is an industry under attack. The past years, it is more often than not the scapegoat of society when it comes to climate change and global warming. With our growing population, a higher demand for food production is inevitable. Therefore, farmers are forced to scale up in order to meet society's demands, but scaling up meat and dairy also results in an increase of waste.

Livestock is a worldwide industry that provides one-third of our global protein intake. The sector employs 1.3 billion people and creates livelihoods for one billion of the world's poor. While the industry is stagnating and even slightly downsizing in developed countries, it is booming in developing countries.[1] Cattle deliver meat, milk, other dairy products… and a dreadful amount of chemicals and greenhouse gases. The world cattle population is currently estimated at about 1.6 up to 1.7 billion units.[1-2] At a rate of 25 to 35 litres of urine and 30 to 60 kilograms of manure per cow per day, they produce all together about 51 billion litres of urine and 76 billion kilograms of manure every day. Cattle alone are responsible for two thirds of the climate impact caused by livestock, mainly due to their emissions of NH_3, CO_2, CH_4, N_2O, and other greenhouse gases.[1-3] Other harmful excretions are nitrate and phosphate that mostly impact the soil and water bodies.[4]

Usually, we point the finger to cow's burps and manure as climatological disasters. They cause chemical reactions that contribute largely to greenhouse gas emissions, air- and water pollution, and soil acidification, but are they really as useless as we think?

Urine contains high levels of nitrogen, while solid manure mainly contains high levels of phosphate, both very beneficial chemicals for adding nutrients to the soil. However, when urine and manure are mixed into slurry, the unique composition of the individual streams is lost, making precise fertilisation more difficult and producing large amounts of ammonia and methane.[5] It all went wrong in the sixties when we started putting faeces and urine together, something nature had so neatly kept separated. Ammonia is produced when the urease enzyme within animal faeces reacts with urea in urine, resulting in ammonia being volatilised, according to following reaction:[6]

$$(H_2N)_2CO + H_2O \rightarrow 2\ NH_3 + CO_2$$

The emission of ammonia has negative health consequences for the soil and for human life. Exposure to high concentrations of ammonia in air causes immediate irritation of the nasal mucosa, throat and other parts of the respiratory tract. This can lead to a decrease in nonspecific immunity in humans, making them more susceptible to opportunistic infections and subclinical diseases, ultimately resulting in reduced overall health and performance.

This phenomenon occurs mainly when the ammonia comes in contact with NO_x and SO_2 products from other industries.[6] When combined with ammonia, little particles originate that penetrate deeply into the lungs and cause diseases, with up to 250 000 deaths every year in Europe alone.[7] Ammonia emissions are also a threat for animal welfare. They cause bronchiolar and alveolar edema, as well as airway obstruction in cows, leading to respiratory distress or even respiratory failure.

Primary separation of faeces and urine in cattle sheds would largely reduce the ammonia and methane emissions. Separate manure products can be better processed and applied more efficiently to reduce negative environmental impact.[5] An innovation of the entire system is necessary to make a change and to go against the industry dominating slurry on which all rules and regulations are currently based. We have to move away from the idea that pumpable slurry is the standard and that ammonia emissions can only be controlled with expensive, energy-intensive air scrubbers.[8]

There are several ways to accomplish the separate waste products. Solutions can be found in a physiological or behavioural perspective. By identifying a precursor or indicator, we can collect both manure fractions separately, immediately after excretion from the animal, though this can be a rather labour intensive and time-consuming process if not managed well. Other solutions that are currently experimented with are the so-called "CowToilet", "weeping wall or weepwall" and low emission floors.

The CowToilet was developed by the Dutch company Hanskamp. It is based on the cow's physiological reaction of urinating when pressure is applied on a certain nerve under the tail. The system works completely autonomic and consists of a small collection vessel that applies mechanical pressure on the cow's nerve and immediately collects the urine before it reaches the stable floor. It is drained through pipelines and collected in large pallet tanks.

The weeping wall concept, developed by the university of California is more established in America and Australia but still has to find its way into European and Asian farming systems.[9] A weeping wall is an engineered basin with one or more perforated walls that form a large dewatering surface area.[10] The slurry is stored in a dedicated containment area with perforated or slatted walls. These walls allow the liquid fraction to seep through into a separate drainage system while retaining the solid fraction that dries into a solid manure layer. The current efficiency of solids retention is about 45%, and recent studies even indicate efficiencies of up to 88% with two-stage weeping wall systems. A system with retention of 65% of solids in the weeping wall already reduces overall methane emissions by 46%.[10] It is crucial in this system though that we take in account that when manure stays in the weeping wall for too long, it starts a fermentation process that causes methane emissions as well. This must be considered to ensure correct and efficient application of the weeping wall.

Many farmers are also experimenting with the implementation of special draining floors that allow urine to pass through while leaving the manure behind, after which it is scraped away.[11] A low emission floor is sloped and has a separate urine channel. It is frequently used together with a robotic scraper. The sloping floor profile is fitted with a gutter for urine under a 1.5% slope. This design allows the urine to drain away quickly, reducing its contact with the faeces, thus minimising ammonia emissions.

Cow urine, if pure, has a considerable value due to the amount of urea and minerals (urine values: nitrogen 6 kg/m^3, potassium chloride 12 kg/m^3) it contains.[9] It can be used as a sustainable alternative for artificial nitrogen fertiliser for crop fields. This would boost the farms circularity and opportunities for value-added products,[13] as available fertilising components in the urine are used more efficiently and more nutrients will be reused on the farm itself, which is mutually beneficial for the farmer and the environment.[12] If the urine is separated from the cow's manure, the formation of ammonia and nitrate in the soil is drastically reduced, while still providing necessary minerals for the soil.[5] This also prevents leaching of unwanted chemicals that could end up in water bodies where they would cause eutrophication, algae blooms and dead zones.[4]

Various studies have also found that cow urine has a number of useful medical applications. Antimicrobial activity of cow urine is comparable with standard drugs such as ofloxacin, cefpodoxime, and gentamycin, against a vast number of pathogenic bacteria, including activity against *E. coli, S. typhi, P. vulgaris, S. aureus* and *B. subtilis.*[14-15] The anti-fungal activity of cow urine is comparable to amphotericin B.[16] and it also has anthelmintic and antineoplastic properties.[15-17]Cow urine even acts as a bio-enhancer for some antimicrobial drugs.[18] It is critical though that risks for zoonotic diseases or intoxication are carefully managed through filtering the beneficial substances from the urine and removing the toxins, pathogens and certain hormones.

Cow manure can be processed in biogas plants or using pocket fermentation, where microorganisms in an anaerobe environment convert biomass into biogas. These installations convert methane out of the manure into sustainable and renewable energy, lowering the company's energy costs as well as its greenhouse gas emissions.[19-20] Animal manure can also be used to improve soil quality after composting. Composting manure makes it more stable and suitable to enhance the soil, resulting in fewer emissions of harmful substances. Injecting it directly into the soil instead of spreading it out over fields reduces ammonia emissions and makes the nutrients more easily available to plants.[21]

A worldwide implementation of the formerly mentioned best management practices on farms and the optimal extraction of useful chemical components for specific uses, will contribute to a sustainable way of manure processing. These management practices can be a valuable implementation in the agri-food chain to evolve in economically, environmentally and socially sustainable ways. The livestock industry experiences an increasing pressure to produce more wealth and less waste. Therefore, it is more important now than ever to walk the way of separate manure streams in livestock and agriculture. Many of these implementations come from accurate chemical research of reactions inside and outside the cow's intestines. Everyday new research and innovations bring us closer to an environmentally sustainable way of food production.

Statement on use of AI

AI was used in the preparation of this essay only for assistance in formatting References in accordance with RSC style guidelines. All sources were found and checked by the author herself.

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Finalist

More fungi, less plastic: how mushrooms could be part of the solution to plastic pollution

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The topic of sustainable plastic alternatives is one of the most active and public-driven areas of materials research today. The food packaging industry is the third largest industry globally and contributes the most to municipal solid waste.[1,2] Therefore, replacing conventional fossil-fuel based plastics with more sustainable packaging materials has a high potential impact. As a result of this, there is a drive to scale-up sustainable packaging materials with the ability to preserve perishable foods and degrade within a suitable timeframe.

Active packaging materials incorporate antimicrobial or antioxidant compounds into the packaging material itself. These next-generation materials aim to tackle issues relating to food spoilage, including the greenhouse gas (GHG) emissions released by food waste, and the occurrence of foodborne diseases.[3] Lipid oxidation and microbial contamination are the major causes of food spoilage - effective active packaging acts to delay these processes, hence preserving perishable foods. Essential oils and natural phenolic compounds such as flavonoids are commonly used as active additives for these materials.[4] When degradable polymers are used to synthesise these materials, they can simultaneously tackle the critical environmental issue of plastic waste. To this end, there is a current trend in active packaging research towards the utilisation of natural, degradable polymers.

Chitin is one of the most abundant, renewable biopolymers on Earth. It is present as a structural component in crustacean shells, insect exoskeletons and the cell walls of fungi.[5] Chitin itself has poor solubility due to the hydrophobicity of acetyl groups and is therefore difficult to incorporate into materials using existing technology. To overcome this, chitin can be converted into chitosan by deacetylation. Chitosan is a natural, biodegradable biopolymer with inherent antimicrobial activity. Materials derived from this biopolymer have many applications including food packaging, biomedical devices, food additives and pharmaceuticals. Industrially, chitosan is derived from chitin extracted from crustacean shells as a byproduct of the seafood industry, in alignment with sustainable development goal (SDG) 14 – focusing on the sustainable use of marine resources. [6] However, recent research has highlighted the potential of utilising mushrooms as an alternative feedstock for chitosan production.

Mushroom cultivation provides an abundant waste stream which could be valorised to improve the sustainability profile of chitosan production. Waste-valorisation is an increasingly popular area of research and the use of agricultural byproducts including mushroom waste adheres to circular economy principles and global sustainable development goals including SDG 12 – focusing on sustainable consumption and production patterns.[6] Furthermore, unlike crustacean chitosan, mushroom-derived chitosan is not limited by seasonal and regional variation. Therefore, the use of mushrooms as a feedstock for chitosan production allows for a constant, stable supply which is beneficial for market demands and associated costs. Additionally, fungal chitosan can be considered as a vegan product due to the absence of animal-based materials, making it appeal to a wider range of consumers. This appeal of this alternative feedstock may be further improved by the absence of allergy triggering compounds such as tropomyosin found in crustacean shells. Moreover, chitosan is generally recognised as safe (GRAS) by the FDA for use as an antimicrobial ingredient in food, and is therefore a promising material for future development, adhering to stringent safety requirements of food packaging materials.[7]

The primary sources of chitin for industrial extraction are crab shells (25-30% chitin) and lobsters (16-23% chitin), as waste products of the fishing industry. Mushrooms, on the other hand, contain 10-26% chitin - often in complex with ß-glucan.[8] Mushroom-derived chitosan may contain ß-glucans as impurities because chitin is covalently bound to these polysaccharides in the fungal cell wall.[9] Indeed, Hirai et al. reported ß-glucan impurities up to almost 40% in their fungal chitosan. The covalent cross-linked network within the fungal cell wall makes it more difficult to extract chitosan without degradation of the polymer chain. This effect may be observed by a lower molecular weight of fungal chitosan when compared to commercial chitosan. Lower molecular weight chitosan generally exhibits better degradability, and mechanical properties can be optimised with techniques such as cross-linking. Therefore, the purification of obtained chitosan samples using glucanase enzymes, which may be associated with high costs and scalability complications, is not necessary to produce successful packaging materials from mushroom-derived chitosan.

Current research focuses on the optimisation of the yield and purity of chitin using different extraction methods. Chitin properties and characteristics vary between fungal species.[10,11] Indeed, Alimi et al. recently reviewed the extraction and quantification methods of chitin and compared yields of chitosan from different species and fruiting parts of mushrooms.[12] Typically, chitin is most abundant in mushroom stalks (stipes), which are a common waste-stream of mushroom cultivation. Several studies have focused on extraction methods with the aim of creating scalable methods for chitin extraction and chitosan production. Usually, the well-established alkali insoluble method (AIM) is utilised to deproteinate and isolate chitin, and this is followed by deacetylation to afford chitosan.[13] This is similar to the method utilised industrially for crustacean chitosan, although with fewer steps as demineralisation is not required for fungal chitosan due to the absence of significant inorganic content such as calcium carbonate. The degree of deacetylation (DDA%) is an important metric to determine during the production of chitosan, where a DDA% greater than 50% confirms that the sample is chitosan rather than chitin. The DDA% achieved affects the properties of resulting chitosan films. Importantly, many studies report that fungal chitosan can be extracted with similar DDA% values to crustacean chitosan.[14]

Chitosan has a good film-forming capability and has been utilised regularly in recent literature to develop biodegradable active packaging materials with properties comparable to those of conventional plastics. Chitosan is often blended with plasticisers, additives or other biopolymers to optimise physiochemical properties. For example, cross-linking chitosan with natural compounds such as citric acid affords materials with improved barrier properties, tensile strength and reduced water-sensitivity, as required for food packaging materials. *Agaricus bisporus* (white button mushroom) is widely consumed, and abundant. This species of mushroom has been utilised in recent research by Bilbao Sainz et al., who utilised brown mushroom stalk bases from mushroom waste and incorporated glycerol and vitamin D-fortified chitosan particles to produce films with similar mechanical and barrier properties to crustacean-derived alternatives.[14] Additionally, Poverenov et al recently utilised fungal chitosan from champignon stipe offcuts and caps to produce edible coatings for fresh cut melon.[15] The group indicated that stipe offcuts, obtained from mushroom industry waste had high yields of chitosan and the coatings improved the physiological properties of the fresh-cut melon. [15] With comparison to animal sourced chitosan, the group reported that the antimicrobial activity of their fungal chitosan was similar and improved the microbial quality of melon.[15] Furthermore, Affandy and Rovina recently reported that their fungal chitosan sample from *Schizophyllum commune* had improved physiochemical properties including higher thermal stability when compared to commercial chitosan.[16]

Global policies should incentivise the sustainable sourcing of materials from biomass and support research and development efforts. Major investment into infrastructure for the production of chitosan and other biopolymers is required in order to meet demands once these materials are widely available on the market. For scalability, it is vital that the packaging materials comply with food contact regulations and are tested rigorously for their ecotoxicity profiles and degradation in different environments. Relating to this, clear labelling of these food packaging materials, once marketed, will be vital to ensure consumers are aware of the optimal disposal route. The replacement of conventional plastics with biopolymers is strengthened by the recent global laws on single use plastics waste, including bans, taxes and levies for specific products by 2030.[17] Current policies include eco-design for sustainable and circular products.[18] Future policies should focus on creating a strategy and econometric model to implement biopolymer materials into major industries, contributing to existing agreements such as the European Green Deal – which aims to implement resource-efficiency and achieve climate neutrality by 2050.[19]

Overall, commercialisation of these materials will rely on the optimisation of mushroom cultivation, extraction and processing methods to reduce environmental impacts. To this end, the use of agricultural waste as the source for mushrooms aligns with circular economy principles and improves the sustainability profile of the resulting materials. Moreover, as demand for chitosan increases with the development of these materials, reliance on fishery waste may become unsustainable. Therefore, mushrooms are a promising alternative feedstock for sustainable chitosan production for application in a variety of materials across different industrial sectors.

Statement on use of AI

No AI was used in the preparation of this essay.

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