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Sustainably transforming waste into valuable products with the chemical sciences

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In its third year, the annual Essay Competition, *Young Voices in the Chemical Sciences for Sustainability*, attracted a record number of nearly 200 entries from around the world. Once again, the winning essays are published in this issue of *RSC Sustainability*. The competition is organized and managed by the International Organization for Chemical Sciences in Development (IOCD) and sponsored by the Royal Society of Chemistry.[1,2] The aim is to highlight the roles of the chemical sciences in promoting sustainability and to encourage young people to develop and present their perspectives through exploring the relevance of scientific approaches to tackling sustainability challenges. The theme of the 2025 IOCD Essay Competition was *From waste to wealth: how chemical sciences can sustainably transform waste into valuable products*.

The Essay Competition was open to entrants who were aged under 35 on 31 March 2025. The entries were assessed by a global team of volunteer evaluators. This year, 43 essays were selected as Finalists based on their quality and relevance to the theme. From within this group, essays that were very highly rated were chosen as Regional Winners, with regions being defined according to the World Bank's 2024 geographic classification.[3]

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Stephen A. Matlin

Stephen Matlin is an organic chemist who served as Professor of Biological Chemistry at City University, London, and Warwick University. He then worked in international development, as Director of the health and education division of the Commonwealth Secretariat, Chief Education Adviser in the UK Department for International Development and Executive Director of the Global Forum for Health Research in Geneva. He is currently a Visiting Professor in the Institute of Global Health Innovation at Imperial College London. He is a Vice-President of the International Organization for Chemical Sciences in Development (IOCD) and leads the group Chemists for Sustainability as well as the Organizing Committee of the IOCD Essay Competition Young Voices in the Chemical Sciences for Sustainability.

Federico Rosei

Federico Rosei has held the Chair of Industrial Chemistry at the University of Trieste since March 2023. Previously he was Professor, Canada Research Chair and UNESCO Chair at the Institut National de la Recherche Scientifique near Montreal (Quebec, Canada). He pursues research on structure/property relationships in nanoscale materials, coupled with efforts in capacity building, mentoring and outreach cross disciplinary and geographical boundaries. He has been Executive Director of IOCD since 2021, where he leads the group Materials for Energy Conversion, Saving and Storage (MATECSS) and is also on the Organizing Committee of the IOCD Essay Competition Young Voices in the Chemical Sciences for Sustainability.

The seven essays designated as 2025 Regional Winners discussed a number of different kinds of waste and different chemistry-based technologies to illustrate their approaches to the theme. As summarized below, their coverage included depolymerization, recycling and upcycling of plastics; upcycling of food and agricultural wastes; capture, storage and utilization of CO_2; and precious-metal recovery and recycling from electronic wastes.

Yick Eu Chew (East Asia and Pacific) (**https://doi.org/10.1039/D5SU90047F**) 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 (Fig. 1). 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.

Frederica Butler (Europe and Central Asia) (**https://doi.org/10.1039/D5SU90053K**) 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 of recovery of components such as precious metals.

João Vitor Paulin (Latin America and the Caribbean) (**https://doi.org/10.1039/D5SU90048D**) 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

Philippe Lambin

Philippe Lambin holds a PhD in physics. He has been professor in the Physics Department of the University of Namur, Belgium, where he is now emeritus professor. Most of his recent research work has been devoted to the electronic properties of carbon nanostructures and 2D materials. Since 2019, he has been a full professor at the Pedagogical Institute for Higher Education in Bukavu, Democratic Republic of Congo. He was elected member of the Royal Academy of Belgium in 2013. He is Treasurer of IOCD and is also on the Organizing Committee of the IOCD Essay Competition Young Voices in the Chemical Sciences for Sustainability.

Lei Jin

Lei Jin holds a PhD degree in Energy and Material Science. She was an FRQNT Postdoctoral Scholar at McGill University, Canada. She also served as a Joint Postdoctoral Fellow (research group leader) at the Institut National de la Recherche Scientifique, Canada. Currently, she is a postdoctoral fellow (Outstanding Postdoctoral Program, research group leader) at the Southern University of Science and Technology, China. She is the Project Manager of the IOCD Essay Competition Young Voices in the Chemical Sciences for Sustainability.

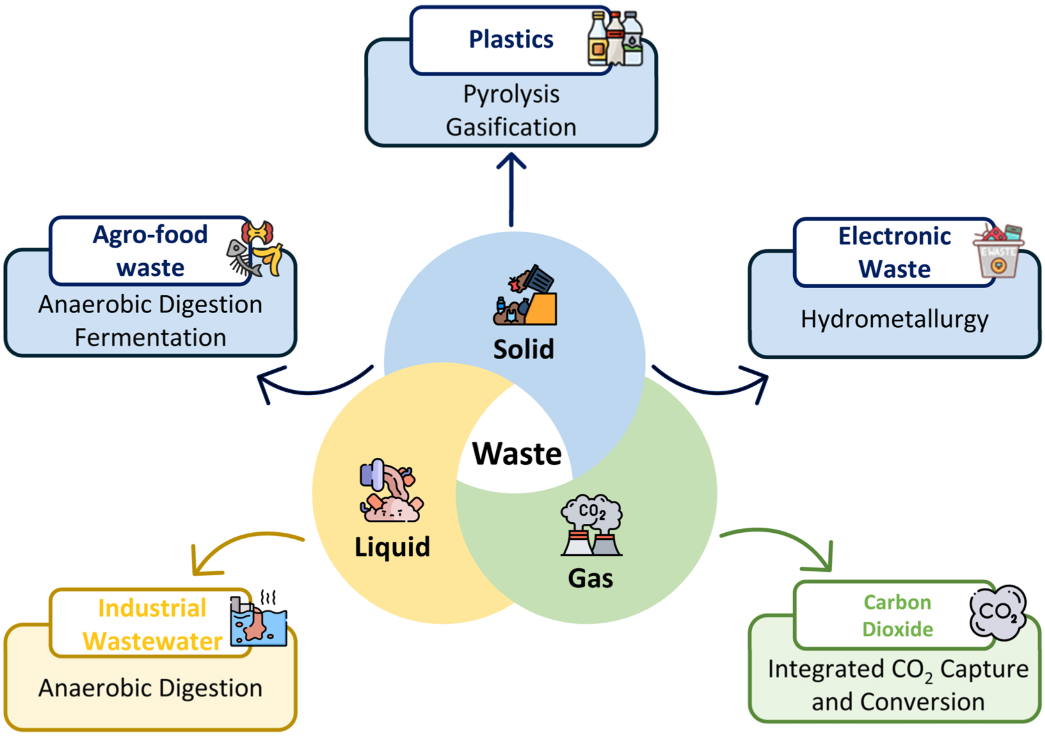

Fig. 1 Summary of different types of waste management through chemical science (from Chew https://doi.org/10.1039/D5SU90047F).

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.

Ahmad Ghanayem (Middle East and North Africa) (https://doi.org/10.1039/D5SU90051D), 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 with 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.

Alexandra Barth (North America) (https://doi.org/10.1039/D5SU90049B) 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 under 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 β-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.

Emal Mathew (South Asia) (**https://doi.org/10.1039/D5SU90052B**) 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 under 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 *via* plastic waste transformation may have.

Emmanuel Oke (Sub-Saharan Africa) (**https://doi.org/10.1039/D5SU90050F**), 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.

Essays from the 36 additional Finalists in the 2025 competition are being published on IOCD's website (**https://www.iocd.org/**) and 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 the 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 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.

The 2026 Essay Competition (**https://doi.org/10.1039/D5SU90054A**) is being launched by IOCD and the RSC in this current issue of *RSC Sustainability*.

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