Molecules to materials for a Sustainable Future

By Centre for Sustainable & Circular Technologies, University of Bath

Every year, the University of Bath's Centre for Sustainable and Circular Technologies (CSCT) hosts a multidisciplinary Summer Showcase to explore the latest developments in sustainable science and engineering. The event is a communion of postgraduate students, academics and collaborators to share their work on tackling the existential issues facing us all.

In the 2022 edition, the Summer Showcase also celebrated the indisputable collaborative and diverse work of Professor Janet Scott, who sadly passed away earlier in the year.

Professor Scott joined the University of Bath in 2010. Her research was at the core of the University becoming a world-leading centre for sustainability research, and she was instrumental in the creation and development of the CSCT. Professor Scott's manifesto flowed throughout the Summer Showcase, and she would have been encouraged by the trajectory of the research efforts being made.

Molecules to Materials – How Science is Enabling a Sustainable Future

Science is key in the global quest for sustainability. We need to find the right solutions to the complex challenges that are threatening our existence on Earth – climate change, pollution, biodiversity loss and poverty.

Sustainable and green chemistry plays a pivotal role in achieving a healthy, satisfying and just life for all people on the planet and generations to come. It is re-inventing fuels, plastics, chemicals, medicines, fertilisers, and many more, to realise non-polluting and recyclable alternatives manufactured using renewable resources with minimal waste.

Other huge scientific efforts are also being made to defossilise society and meet net zero targets – all of them designed to reduce the environmental impact of carbon dioxide emissions.

And although immense progress is being made, it is only the beginning.

Why chemical pollution demands urgent action

Synthetic chemicals are a fundamental part of everyday life. They exist everywhere and in everything – food, clothes, tools, furniture, cosmetics, medicines – but despite their usefulness, we now know their huge negative impacts on both our health and the environment.

The chemicals industry commands extensive global economic value, as **Dr Camilla Alexander-White, Lead Policy Advisor – Chemicals Policy at the Royal Society of Chemistry,** explains:

“Chemicals is the second largest manufacturing industry in the world. The 2020 UN Global Chemicals Outlook Report found that between 2000 and 2017, the global chemical industry’s production capacity doubled from 1.2 to 2.3 billion tonnes. In fact, 95% of all manufactured products contain inputs from the chemicals industry, and their global sales including pharmaceuticals totalled $5.68 trillion in 2017.

“And it shows no sign of slowing down. Chemicals production and consumption is set to double by 2030. The Royal Society of Chemistry’s position is that, if production doubles, pollution must not double consequently – the world’s nations should aim to significantly reduce chemical pollution from current levels, but this requires a balanced and coordinated approach.”

There is an increasing and disturbing body of evidence documenting negative impacts of pollution. Citing The Lancet Commission, Dr Alexander-White shares some frightening statistics:

“Pollution is responsible for 9 million premature deaths (2019 data) – 1 in 6 deaths worldwide – per year. From those, air pollution causes over 6.5 million deaths globally each year. And from those, lead (Pb) and other hazardous chemicals are responsible for 1.8 million deaths globally. Deaths from toxic chemical pollution have risen by 7% since 2015 and by over 66% since 2000.

“Despite the numbers, in the UK we can live healthy lives. 92% of the global pollution-related deaths take place in low and middle-income countries where other countries – including the UK – transport their waste.”

The amount of chemical pollution also threatens the stability of the global ecosystems upon which humanity depends. Plastics are of particular concern.

“Since 1980, plastic pollution in the oceans has increased tenfold,” says Dr Alexander-White. “The rate of global change in nature during the past 50 years is unprecedented in human history, with one million species threatened with extinction (IPBES 2019).”

But how can we limit the negative effects of chemicals that have become part of our everyday life?

The Royal Society of Chemistry is leading the way on this urgent matter and is calling for a sustainable chemicals revolution, as Dr Alexander-White explains:

“Previous international attempts at the massive undertaking of addressing chemical pollution have not worked. For the world to solve the major environmental and health challenges we face, there must be a sustainable chemicals revolution through responsible innovation and clean-up. We can only achieve this through senior-level engagement with the chemical sciences community and an authoritative, intergovernmental science-policy interface at a global level.

95% of all manufactured products contain inputs from the chemicals industry and their global sales totalled $5.68 trillion in 2017.

“Early in 2020, we engaged with scientists in our community to develop our vision for a chemicals strategy, relevant to any nation in principle. We identified four pillars on which any chemicals strategy must be based: education, innovation, circular economy and regulation. National governments must invest in these areas and create a responsible framework of action for chemicals management.

“We highlighted the growing consensus and need for a new global science panel for chemical pollution – an independent, intergovernmental science-policy platform for chemical and waste management with a similar status to IPCC (the Intergovernmental Panel on Climate Change) and IPBES (the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services), to enable science-informed, multidisciplinary, global coordination and action on chemicals pollution, protecting our planet and saving millions of lives.”

And in March 2022, the United Nations Environment Assembly UNEA-5 agreed to establish a science-policy panel on chemicals and waste and to prevent pollution.

“It is a landmark resolution that begins a 2 to 3 year phase of work to establish a new panel for chemicals, waste, and pollution. It is anticipated that a science policy panel will be in action in 2025 and we look forward to engaging with the science community as the programme evolves,” adds Dr Alexander-White.

Looking at the big picture to tackle climate change

The chemical industry is the third largest industrial emitter of CO2, the greenhouse gas emissions that lead to climate change. How can we tackle climate change as part of our efforts to reduce the impacts of chemical pollution?

"Deaths from toxic chemical pollution have risen by 7% since 2015 and by over 66% since 2000. (...) 92% of the global pollution-related deaths take place in low and middle-income countries where other countries - including the UK - transport their waste"

Dr Camilla Alexander-White

Juliet Davenport, Founder of Good Energy, says we need to look at the big picture: “To tackle climate change and support the transition to net zero we need to consider the wider context. Over the last decade, the UK has spent £0.2 billion on energy R&D compared with £4.5 billion on pharmaceuticals. This lack of spending on energy has meant the UK is in catch-up mode, on technology and systems innovation.

“The UK’s infrastructure was built for a high-carbon world. The leadership challenges are how to adapt to a low-carbon one using innovation, design and enterprise. Part of this is investing in future electricity networks and in understanding how to best operate them nationally and locally, and how to bring innovation in at pace to support this.

“Gas networks cover 80% of the UK’s households. This needs to change, but there’s no easy solution. Our houses are some of the poorest insulated in Europe, and the processes and materials for dealing with the retrofit market still seem to be behind the curve. Work is urgently needed to find a way forward to retrofitting and supporting low-carbon heating.

“Our road infrastructure was built around the internal combustion engine. We need a new infrastructure, built around electrical and hydrogen networks rather than fossil fuel networks. Neither are straightforward and, although the roll out has started, it will need to continue at pace."

This sounds like a mountain to climb – and in a very short time – to reach net zero. There have been some positive advances, particularly within the areas of finance and regulation, where longer term financial policy instruments have brought in significant investment.

“The government aims to increase offshore wind capacity from 11GW to the significantly increased 50GW by 2030, requiring huge investment in onshore and offshore infrastructure in England, Wales and Scotland.

“Barriers to solar development have been removed, which will lead to large-scale solar and commercial rooftops being prioritised by investors. We’re also seeing significant focus and a future investment ambition of producing 25% of our electricity from nuclear energy. Furthermore, the government has doubled the UK’s ambition to realise up to 10GW of low carbon hydrogen production capacity by 2030, subject to affordability and value for money, with at least half of this coming from electrolytic hydrogen,” says Davenport.

What is the chemicals industry doing to address sustainability?

The chemicals sector is the largest industrial user of oil and gas, and it has the third largest industrial carbon footprint. It burns about 50% of the fossil fuels it uses as energy, using the rest as feedstock for products such as plastics, with emissions released when they reach the end of their life. Add in the environmental impact of plastic and 'forever chemicals' such as Teflon, and the situation becomes very grave. So, what can industry do to reduce its impact on pollution and climate change?

Croda is the world's leading specialist manufacturer of high-performance oleo-chemical ingredients and technologies. These are supplied to global brands operating in markets such as beauty and personal care, household cleaning, pharmaceuticals, crop protection and seed enhancement.

Sarah Davidson, Group Sustainability Coordinator – R&T at Croda, talks about going the extra mile in their strategy:

"We want to go beyond doing what is 'necessary' to have a positive impact on the climate, land and people. We have aligned our innovation programme with the 12 Green Principles of Chemistry and the United Nation's SDGs (Sustainable Development Goals) to inspire the production of chemicals which are safe and sustainable by design. This encompasses our goals to decarbonise, provide low-carbon footprints and deliver sustainability benefits to our customers and the consumer.

"Our sustainability strategy sets our commitment to be the most sustainable supplier of innovative ingredients by 2030. We focus on the impact that we want to have to make a difference and find the solutions – and this is ingrained within our R&T.

"Since the launch of our commitment we've introduced minimum sustainability criteria for all innovation projects and introduced a R&T checklist to assess the sustainability impact of our new products. Our goal is to bring together safety, sustainability, and performance," explains Davidson.

"In new product development, we're paying more attention to the sustainability impact of the raw materials and product manufacture – considering biobased content and ways to minimise carbon, energy, and water use. We continually judge the intrinsic and extrinsic sustainability output through product development, determining what the biodegradability or ecotoxicity is.

"By 2030, over 75% of our organic raw materials by weight will be biobased, sequestering carbon from the atmosphere as they grow. We're going to achieve this by replacing existing petrochemical raw materials with renewable alternatives, new product development using biobased ingredients and the discovery of new platform chemicals from biogenic origin.

"We're thinking outside of the box about how we can re-write the rule book when it comes to sustainability, and instead of relying on traditional chemistry we're exploring new sustainable chemistry and industrial biotechnology processes," says Davidson.

Industry and academia working together to find sustainable solutions

Commitments such as these are resulting in some pioneering technical solutions to tackle pollution, but it requires industry and academia to work collaboratively on research and innovation to implement and bring solutions to market quickly.

The Innovation Centre for Applied Sustainable Technologies (iCAST) is a £17m unique collaboration between industry and academia set to accelerate the translation of green technologies into commercial applications in order to address challenges such as the climate emergency, sustainable development, and plastics pollution.

Hosted within the CSCT, it brings together industry with the research expertise at the universities of Bath and Oxford, the High Value Manufacturing Catapult's Sustainability Partnership, innovation experts at SETsquared, Local Enterprise Partnerships and investors.

iCAST is currently engaged in R&D projects centred around circular plastics, sustainable manufacturing, renewable and biobased feedstocks, and sustainable engineering materials for composites and the built environment.

One project currently in operation at iCAST is the development of biobased tree guards as an alternative to the use of petrochemicals. Over 40% of new trees are damaged or destroyed by wildlife, and plastic tree guards are used to help alleviate this issue. However, they are not collected or recycled, therefore contributing to environmental plastic waste.

Dr Ben Groombridge, iCAST Specialist Technician from the University of Bath, explains:

"Our biobased and biodegradable tree guards aim to minimise the environmental impact of major tree planting programmes.

"To create the material, we use epoxidized vegetable oil (EVO) obtained from biomass, which we then crosslink with citric acid obtained from citrus fruit. The result is a robust but biodegradable protective structure built from renewable resources.

"These materials have similar properties to existing tree guards – they are water and acid resistant for more than three months, soil resistant for at least a month and UV stable for at least a year.

And, most importantly, they do degrade under certain lab conditions that indicate good long-term degradability in nature."

Another example of a research centre bringing together industry and academia is the Industrial Decarbonisation Research and Innovation Centre (IDRIC), which is at the forefront of the UK's ambitions to cut industrial greenhouse gas emissions.

Heriot-Watt University and the University of Bath's CSCT co-lead this £20m decarbonising initiative that works alongside more than 140 partners from academia, industry, and government. IDRIC's core objective is to create the world's first net zero emissions industrial cluster by 2040 and four low-carbon clusters by 2030.

The team at IDRIC are involved in over 40 research and innovation projects centred around balancing carbon emissions with local clusters, decarbonising through reviewing land use, and producing high-value chemicals.

Dr Lewis McDonald, IDRIC Researcher from the University of Bath, explains some of the key research projects that are ongoing:

"Life Cycle Assessment (LCA) is a powerful tool for quantifying the environmental footprint of industrial products and processes. We're developing a framework to apply LCA techniques across IDRIC projects, so we can identify opportunities to reduce greenhouse gas emissions. As part of this, we're looking at new ways of acquiring data to make sure that all LCAs conducted at IDRIC are totally transparent and provide a solid base for moving forward with LCA development.

"There are shortcomings that need to be addressed, for example LCAs don't consider the temporal and spatial aspects of carbon capture. If you were to capture CO2 and store it underground, you could do so for hundreds or thousands of years. Whereas, if you were to capture it and then turn it immediately into a biofuel, you may only get 3-4 months of capture. So, can we maximise the time that the CO2 is stored and the different methods of doing so?

"Another shortcoming with LCA is its limited ability to handle uncertainty and sensitivity in the data. We're looking at ways to apply analysis techniques that'll enable scientists to gain a more accurate picture.

"We're also applying our LCA research to several projects, including our work on Volatile Fatty Acids (VFAs), which are key platform chemicals, produced from fossil fuels, used in a multitude of industries – chemicals, pharmaceuticals, food and agriculture. With colleagues in the University of South Wales, we're developing pathways to produce VFAs from industrial waste instead. As part of this project, we've built a VFAs Factory for Decarbonisation – a reactor on site at Tata Steel in Port Talbot that's capable of producing materials such as bioplastics.

"Bio-Balance is another project focused on the South Wales Industrial Cluster, working with Tata Steel and other partners including Welsh farming unions and Natural Resources Wales. Bio-Balance's objective is to identify local challenges and demonstrate potential for carbon capture. Within a controlled environment, waste and by-products such as heat, light and CO2 from industry can be repurposed for use in agricultural processes and community developments," explains Dr McDonald.

Naturbeads is a spin-off company that began at the CSCT in 2018 with the late Professor Janet Scott and her colleagues Professor Davide Mattia and Dr Giovanna Laudisio. They worked on finding a natural alternative for plastic microbeads, which are added to cosmetics and personal care products and then washed away into our sewers and oceans, damaging the marine ecosystem.

The solution designed by the CSCT team was a plant-based biodegradable bead made from cellulose. Naturbeads is now working with industrial partners to introduce cellulose beads in multiple applications, including personal care and cosmetics, paints and coatings, medical, oil and gas, and biocatalysis applications.

Dr Davide Califano, Protein Chemist at Naturbeads, talks about his role in the company, working on the biocatalysis applications: "I work on designing and developing enzyme-based biodegradable cellulose beads as biocatalysts.

"We've explored the antimicrobial properties of cellulose beads when we functionalise them with certain enzymes. These molecules, extracted mostly from fungi, can be used to capitalise the

Naturbeads' plant-based biodegradable beads can be used in multiple applications, including personal care and cosmetics, paints and coatings, medical, oil and gas and biocatalysis applications.

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Juliet Davenport OBE

transformation of glucose into gluconic acid and nitrogen peroxide, which is an antiseptic and antimicrobial compound. So, potentially these beads could be used to fight antibiotic resistance.

Cellulose beads open many other possibilities in biotechnology including enzyme immobilisation, ionic exchange, cell scaffolding and drug release."

Another example of the versatility of these biobeads is their use in the tyre industry, as tyre wear is a major source of river and ocean microplastics. In June 2022, Naturbeads secured funding to collaborate with the University of Salerno, Italy, to explore the applications of its cellulose beads within the tyre industry to improve sustainability and decrease its contribution to microplastic pollution.

The CSCT has also contributed to research into the material PLA, a bioplastic made from lactic acid. This is a long-term collaboration with TotalEnergies Corbion, who are manufacturing PLA for use in applications as diverse as packaging, consumer goods, 3D printing, clothing and automotive applications.

PLA is both biobased (made from natural raw materials), recyclable and biodegradable (compostable under industrial composting conditions). It is one of the first renewable polymers able to compete with conventional polymers in terms of performance, and it is also three times less carbon intensive to manufacture.

The CSCT is undertaking laboratory studies to develop further the properties of PLA – from altering PLA's thermal properties to expanding its end-of-life options and adapting its technical performance for new markets. TotalEnergies Corbion has meanwhile commercialised advanced recycled PLA and PLA products remain certified industrially compostable.

Dr Gerrit Gobius du Sart, Corporate Scientist at TotalEnergies Corbion, has led the collaboration with the CSCT from the beginning:

"PLA research began in the 1970s, when it was developed for biomedical applications such as poly(lactic acid) stitches, and over the past three decades the industry has been preparing to upscale for technical applications.
Right now, there's a lot of interest in the application of PLA for single-use packaging, especially in the food and drink industry, but also in the non-woven fabrics market.
Moreover, PLA has an enormous potential to replace many other conventional plastic applications, including durable products such as electronics. The use of PLA can have a major impact on global plastic waste, because its carbon footprint is 75% smaller than conventional plastics."

A collaboration between the CSCT and the University of Sao Paulo, Brazil, is working to optimise the sustainable production of renewable liquid fuel – cellulosic ethanol – for mass use.

Most of the biofuel in Brazil is blended into gasoline, and this has helped reduce the rate of petrol consumption. In fact, the production and combustion of ethanol reduces greenhouse gas emissions by 12% compared to fossil fuels, making it a desirable ally in the fight against climate change.

Sucrose from sugarcane has been the primary feedstock of Brazilian biofuel (ethanol) for over 35 years. But sucrose is also highly valued for food use, so scientific interest turned towards using the non-edible components of sugarcane for production of cellulosic ethanol.

The current disadvantage of cellulosic ethanol is its high production cost. It's a more complex process that requires more steps compared to first generation sugarcane-based ethanol, and this has impeded its commercialisation so far.

The CSCT-Sao Paulo project is exploring ways to boost bioconversion rates and improve the yield of this process, using complex carbohydrate active enzymes (CAZymes). These enzymes can increase the catalytic potential of the microbial communities used in hydrolysis and the efficiency of the pre-treatments used in bioethanol production.

Professor Igor Polikarpov, Sao Carlos Institute of Physics at the University of Sao Paulo, speaks about the progress Brazil is making with its biofuel production: "For Brazil, bioeconomy is not a choice – it's a necessity. Currently the country has well-established first generation (1GE) ethanol production facilities, which produce ethanol from sugarcane. These generate large amounts of biomass that can be used for what is known as second generation ethanol (2GE) production, which uses sugarcane bagasse and trash obtained from the processing of sugarcane for ethanol or refined sugar production. Several industrial and pilot-scale facilities for 2GE have already launched in Brazil.

"Pre-treatment protocols, enzymatic mixtures and fermentation procedures still must be optimised to make Brazilian 2GE production sustainable. A solid scientific and technological base and established 1GE agro-industrial sector will (hopefully) make Brazilian bioeconomy a reality."

Efforts to commercialise cellulosic ethanol are happening around the world and it is hoped that in the future there will be opportunities to use it in other applications, such as sustainable aviation fuel and biobased chemicals.

Sucrose from sugarcane is the primary feedstock of Brazilian biofuel, but non-edible alternatives are needed

Professor Janet L. Scott (1964-2022)

A word about Janet

This year's showcase was inspiring for many reasons – the progress made in fundamental research in chemical technologies that will shape the products and processes we depend upon, the value of collaborative research, and the actions taken by industry and professional bodies that will pave the way towards a more sustainable future.

But crucially, this event also celebrated the life and work of Janet Scott – a brilliant researcher who dedicated her life to sustainability and truly believed in crossing the boundaries of traditional disciplines in industry and academia to spark creative problem-solving.

She was passionate in all aspects of her life. Her colleagues and friends described her as someone who would not shy away from delivering hard truths or unpopular opinions if she thought the occasion demanded them. Her mentees and students would probably highlight how much she cared about their development and how well she navigated the fine line between nurturing and pushing them, so they would deliver the best they could. Her close friends talk about her cheeky sense of humour, her green fingers and her love for long walks and fine dining.

Janet built robust, long-lasting relationships with friends and colleagues and her contributions reached much beyond the field of sustainable chemistry. This was clearly demonstrated by the number of people who attended this event to pay a tribute to the scientist and the person that she was.

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