RSC Sustainability

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Cite this: *RSC Sustainability*, 2024, **2**, 3589

DOI: 10.1039/d4su90046d

rsc.li/rscsus

Towards a net-zero future: the chemical sciences across technology, education, and policy

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There is no denying the significant impact that the chemical sciences have had in the rapid advancement of the energy, manufacturing, and agricultural sectors. Innovations in materials, processes, and technologies have been instrumental to these industries that underpin modern society, but these developments have also been accompanied by an unprecedented change in climate that will have catastrophic consequences if not addressed immediately. Achieving a net-zero future relies on global multisectoral efforts, of which the chemical sciences, through technology, education, and policy, will play an indispensable role.

The energy, manufacturing, and agricultural sectors are consistently ranked among the leading sources of global greenhouse gas (GHG) emissions.[1] Increased concentrations of these emissions trap heat within the earth's atmosphere, leading to sea level rise, low crop yield, and extreme weather events. Arriving at a comprehensive understanding of the situation would not be possible without the chemical sciences. It is because of chemistry that there is a growing body of knowledge of the mechanisms by which atmospheric molecules transform and influence air quality and the climate.[2] As the central science, the chemical sciences have also served as the foundation for analytical instruments that allow for emission monitoring, which is useful for identifying sources of emissions and tracking trends over time, and atmospheric modeling, which aids in studying how pollutants interact under different conditions across spatial and temporal

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scales.[3] These analyses help inform policies by providing insights into where and what kind of interventions should be prioritized.

Among possible interventions is the implementation of technological solutions. In decarbonizing energy production, this means deploying technologies that will facilitate the transition to renewable energy sources such as wind or solar. The chemical sciences contribute to this through the design of clean and cost-effective technologies for energy generation, solutions for energy storage, and processes for extracting, refining, and recovering necessary resources.[4] In areas where carbon-based energy has yet to be phased out, the chemical sciences form the basis for best available techniques which are adopted in power plants to meet stringent emission standards. These include retrofitting the facility with desulfurization or denitration technologies that treat GHGs before release; substituting existing processes or materials with those that produce less or no emissions, such as the use of coal with low sulfur and low ash content; and adopting carbon capture techniques to sequester emissions already in the atmosphere.[4,5] These developments are essential, as sustainable energy systems are a prerequisite for emission reductions in other sectors.

Aside from clean energy integration, large-scale manufacturing processes, such as those for metals, chemicals and petrochemicals, and other materials, can benefit also from innovations that enable circular production, specifically, mechanisms that reduce natural resource consumption, allow for the reuse of materials and parts, and facilitate recycling for added value creation and responsible waste management.[6] To this end, contributions from the chemical sciences focus on researching and developing novel substances and processes that make this possible. A few examples of these innovations include redesigning products to promote effective recycling and developing bio-based materials from renewable resources that biodegrade rapidly without compromising performance.[7]

Similar approaches will also be required to address emissions from agriculture, where activities such as livestock farming, crop residue burning, and the use of nitrogen-based fertilizers are common sources of emissions.[1] Aside from the previously discussed solutions, there are several ways the chemical sciences can be used to eliminate emissions from this sector. Among them is the creation of feed additives to reduce CH_4 emissions belched by ruminant livestock;[8] the development of agricultural waste management strategies, including biofuel production and mushroom cultivation, as inexpensive alternatives to agricultural waste burning;[9] and the optimization of field management practices to mitigate N_2O emissions resulting from the increased application of nitrogen fertilizers.[10]

While it is important that scientists have the necessary skills and knowledge to pursue these projects, it is just as important that they possess the right attitudes to act in accordance with the objectives of sustainable development. One way to instil these values in them is through the integration of green chemistry into both laboratory and lecture classes.[11] By training scientists to give careful consideration to the origins of atoms and how they transform, chemical scientists can better develop materials and processes to maximize resource efficiency and minimize adverse health and environmental impacts.[11] Teaching sustainable chemistry goes hand-in-hand with a reevaluation of conventional pedagogical tools. For example, while the Carnot engine is a useful tool for teaching thermodynamics, there is a need to develop alternative non-CO_2-producing models that can further enrich green chemistry education.[12] Integrating sustainable practices and concepts into the curricula can have a profound effect on the worldview of young scientists, but there are still ways to ensure this shift in mindset extends beyond the scientific community.

The chemical sciences are inherently and socially responsible for ensuring the public is aware of the impacts that the energy, manufacturing, and agricultural sectors have on their lives and future.[13] This includes addressing misconceptions and dismantling harmful long-running narratives that insist a net-zero future is too far-fetched. Public outreach through workshops, seminars, and media campaigns are important steps; but more than simply presenting facts and evidence in an engaging manner, bridging the gap between content and impact can be done more effectively when scientists actively engage with their local communities.[14] Having an intimate understanding of the local context allows for a more integrated approach to raising awareness in a way that deeply resonates with target audiences and fosters a genuine concern for climate change. Community-centered approaches not only improve science literacy but also promote evidence-based public discourse, inspire movement, and help challenge prevailing narratives that hinder progress in sustainable development.

However, it will take more than new technologies and effective communication to achieve net-zero emissions at the scale and level of urgency needed. In order to ensure every sector does its part, it is imperative that the chemical sciences play an active role in public policy. When the appropriate policies are in place, industries are offered greater incentives to adopt pollution control technologies, adhere to certain product design requirements, and implement more sustainable practices, leading to greater strides in emission reduction efforts. In turn, this demand for sustainable solutions stimulates the pursuit of breakthrough innovations, which can be accompanied by increased attention and funding for research activities. Unfortunately, public policy is subject to numerous social, economic, and environmental processes, which are often uncertain and difficult to control—and science, no matter how reliable and compelling, is only one of many factors at play in the policymaking process.[15]

In addition to having technical expertise, successfully navigating the science–policy interface also requires connections and a high level of persistence.[15] Aside from running for government positions, another effective way to influence policy is by working with environmental organizations that advocate for science-based solutions. These organizations, depending on their scale, may already have resources, established networks, and a firm understanding of the target sectors' landscape. These groups provide an opportunity to connect and understand the interests, challenges, and experiences of key stakeholders, including, but not limited to, consumers, policymakers, power plant owners, factory workers, farmers, and members of vulnerable communities. By working with such organizations, whether as a volunteer, a consultant, or a collaborator, scientists can provide more grounded insights into overcoming technical challenges and developing strategies for decarbonization.[16,17] This partnership can help better maximize co-benefits and ensure the fairness and inclusivity of the net-zero transition.

It is clear that there are multiple roles for the chemical sciences to play in achieving net-zero emissions. Technological innovations are crucial to understanding and controlling emissions from across the energy, manufacturing, and agricultural sectors, but the role of the chemical sciences is not confined to the laboratory. The chemical sciences will also play a key part in nurturing the next generations of scientists, strengthening public awareness, and contributing scientific perspectives to the policymaking process. Achieving net-zero emissions is contingent on these contributions; the challenge now is to embrace these opportunities and do our part in securing a sustainable future for generations to come.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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

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