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From lab to landscape: the role of chemical sciences in sustainable technology

Yana Walia

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The Industrial Revolution in the 1750s marked a pivotal period in history, distinguished by significant economic shifts but also the rapid development in scientific and technological advancement. It was also a beginning point for humanity's gradual, barely noticed, part in environmental decline as greenhouse gas emissions steadily increased, changing temperatures and weather patterns. With atmospheric carbon dioxide reaching levels 50% higher than pre-industrial concentrations in 2021, it is imperative that action is taken.[1] More and more traditional practices are being replaced with newer technologies to meet the objectives of sustainable development, defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" by the UN Brundtland Commission. This shift is aided by rising advocacy for sustainability, decreasing our reliance on carbon-based fuels and eco-friendly techniques. However, as the consequences of emissions are rooted in science, it will be science, particularly the chemical sciences, that will solve the question: how do we sustainably reduce our impact on the Earth?

The chemical sciences have already demonstrated their capability through innovative concepts, to integrate renewable energy sources, such as wind, solar and hydropower, into our existing generators. Transition towards a blend of renewable energy sources can significantly decrease greenhouse gas emissions. However, evaluating the pros and cons from both chemical and socio-economical perspectives is essential to allow large-scale implementation. Whilst renewable energy sources can be replenished, create employment opportunities, and have a lower maintenance cost, their reliability and efficiency are barriers to their use as primary energy sources, especially with the growing energy demand.

Hydrogen fuel cells remain an exception to these disadvantages as they are a notable innovation in clean energy, supporting zero-carbon strategies by only producing water and heat as the products of an electrochemical reaction. The high efficiency and easy-to-resource reactants allow for versatility in many applications. With the addition of hydrogen fuel cells to vehicles, the shift towards zero-emission transportation would be imminent, reducing pollution from a significant sector. Still, it is crucial to consider

Brighton College Abu Dhabi, United Arab Emirates. E-mail: yanawalia2006@gmail.com

Yana Walia

Yana Walia, originally from India and currently residing in the UAE, is an A-level student studying biology, chemistry, and mathematics, set to graduate in 2025. She is keen to pursue undergraduate studies in biochemistry, driven by her aspiration to study the sciences at a higher level. Beyond her school curriculum, Yana is interested in gene modification. She is independently researching various genetic editing mechanisms and evaluating their potential applications as part of an extended project.

not only the fuel cell itself but also the manufacture of the reactants. Steam methane reforming (SMR), responsible for producing approximately 95% of hydrogen globally, requires the splitting of methane molecules, which releases carbon dioxide.[2]

To address this, SMR is often paired with carbon capture technology. Carbon capture and storage (CCS) are technologies that play a crucial role in removing carbon dioxide (CO_2) from sources, such as industrial plants, by compressing and storing CO_2 underground beneath several layers of impermeable rock.[3] This process is particularly significant in modern industrial settings, given the staggering 40 billion tons of carbon emissions released in 2023.[4] Furthermore, as most CSS technologies are adaptable, they can easily be fitted onto many industrial plants,[5] inciting more companies to make sustainable choices. Despite its benefits, adopting CSS may take longer than previously thought due to its relatively high costs, which could dissuade companies from investing. Moreover, the potential long-term environmental risks of storing CO_2 underground include leakage into groundwater or the atmosphere, ultimately reducing efficiency.[6]

The research used to create and improve CCS lies in the principles of green chemistry, which is the concept of reducing the generation and release of waste substances into nature. With 12 fundamental principles, this concept is vital to manufacturing and industry, with new research on energy-efficient technology and safer chemistry for accident prevention, helping to build more sustainable pathways.

These pathways include converting greenhouse gases into other substances, such as green methanol. Biocatalysts can catalyse a three-step conversion from CO_2 to methanol, in line with the ninth green chemistry principle of increasing the use of catalysts and, due to methanol's benefits, this is the preferred reaction to reducing CO_2 to carbon monoxide. Methanol fuel is considered more environmentally friendly than conventional fuels as it cuts CO_2 emissions by 95% and decreases NO_2 by up to 80%.[7] In addition, it is a common chemical feedstock for producing ethylene and propylene, the two most common petrochemicals in the methanol-to-olefin (MTO) process.[8]

The agricultural industry is slightly more complicated as it contributes to greenhouse gas emissions, but is also negatively impacted by them. It has already been proven that greenhouse gases lead to climate change, which then has consequential effects on agriculture. Examples include changes to precipitation patterns, extreme weather, and water availability, which could decrease agricultural productivity. This could ultimately lead to decreased food security, especially with the growing population; therefore, reducing greenhouse gases to limit these effects is crucial.

Despite this, the sector adds emissions through various means, including tillage, transportation, and manure application. However, enteric fermentation, the digestive process of ruminant animals where microbes decompose and ferment carbohydrates, is one of the primary producers of greenhouse gases in the sector, specifically methane. To emphasise the importance of methane production from enteric fermentation, research in 2018 revealed that methane constituted 45% of greenhouse gas emissions in the EU.[9,10]

Current solutions include directly manipulating animal feed composition and quality to allow it to contain higher fermentable carbohydrates, which decrease methane production.[11] Whilst this is a relatively simple change, it may not currently affect global greenhouse gas production. Given that many countries with the highest methane emissions, such as India and Brazil, are developing countries, it would be challenging to implement this strategy fully. Abhishek Jain, a researcher at the Council on Energy, Environment and Water, stated that agriculture in India is the "biggest source of methane, but it is one of the hardest sectors to abate".[12] This is due to many agricultural workers being below the poverty line and unable to afford higher-quality feed, inadvertently increasing emissions.

Other strategies involve affecting the microbes within the digestive system through special additives, feeds, or vaccines, but it was found that the microorganisms could adapt quickly to these changes and overcome them. However, one feed additive, 3-nitrooxypropanol (3-NOP), has been shown to be highly effective in reducing the levels of enteric methane formed. The additive works by acting as an inhibitor for methyl-coenzyme M reductase (MCR), the enzyme that forms methane, and interfering with the process of methanogenesis in rumen archaea.[13] Furthermore, 3-NOP does not appear to adversely affect animal performance, inciting further support. By reducing enteric methane formation, 3-NOP has the potential to cut emissions from a major sector, decreasing the rate of climate change and allowing for a sustainable future.

In summary, the future of sustainable technologies and innovations lies in the hands of the chemical sciences. Considering different socio-economic issues and policies, it is possible to distribute technologies to allow other industries to reduce emissions. These machines can be enhanced using the 12 fundamental principles of green chemistry to optimise sustainability while also shaping a more environmentally conscious and resilient future for Earth.

Conflicts of interest

Grammarly Premium AI and ChatGPT were used to enhance the language and readability of this essay. AI software was not used to analyse data, draw scientific conclusions or write sections of the essay, nor did AI use create false references or provide untrue information.

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