International
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Chemical Sciences
in Development

YOUNG VOICES
IN THE CHEMICAL SCIENCES
FOR SUSTAINABILITY
2024

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

Decarbonizing energy conversion and eliminating the generation or release of greenhouse gasses from large-scale manufacturing and agricultural processes

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

International Organization for Chemical Sciences in Development
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Young Voices in the Chemical Sciences for Sustainability 2024
Winners and Finalists of the 2024 essay competition:
How can the chemical sciences contribute to 'decarbonizing' the energy sector and to eliminating the generation or release of greenhouse gasses from large-scale manufacturing and agricultural processes?

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Introduction

Stephen A. Matlin, Federico Rosei, Philippe Lambin and Lei Jin
International Organization for Chemical Sciences in Development (IOCD), Namur

IOCD's mission is to promote the pursuit and application of the chemical sciences for sustainable, equitable human development and economic growth, through repositioning chemistry as a science for the benefit of society and by promoting the role of the chemical sciences in sustainable development. IOCD's action groups[1] cover a range of strategically chosen activities to advance this mission, including through its working group on Materials for Energy Conversion, Saving and Storage (MATECSS),[2] led by IOCD's Executive Director Federico Rosei, which 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. An international group of chemists in IOCD's action group *Chemists for Sustainability* (C4S)[3] has served 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. IOCD's newest Working Group, on Green and Sustainable Electronics,[5] addresses the challenges of material sustainability and environmental protection in one of the most rapidly expanding fields of technology in the 21st Century. The Working Group on Chemistry Education 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 two global projects to help embed systems thinking in chemistry education as a key approach to sustainability.[7]

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*.[8] Organized and managed by IOCD, the aims of the competition are 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.[9] The theme of this first Essay Competition was "*How can the chemical sciences lead the stewardship of the Earth's element resources?"* and the six essays designated as 2023 Regional Winners were published[10] in the October 2023 issue of *RSC Sustainability*, with the essays from a further 15 finalists being published by IOCD in a Compendium.[11]

The 2024 IOCD Essay Competition[12] was on the theme "*How can the chemical sciences contribute to 'decarbonizing' the energy sector and to eliminating the generation or release of greenhouse gasses from large-scale manufacturing and agricultural processes?*" It attracted 76 valid entries (39 female, 37 male) from 32 nationalities, with ages ranging from 15 to 34. After evaluation by volunteers from around the world recruited by IOCD, 24 essays were selected as Finalists and further examined by the judging panel, which selected seven as the Regional Winners with regions being defined according to the World Bank geographic classification.[13] The seven essays designated as 2024 Regional Winners were published[14] in the December 2024 issue of *RSC Sustainability* as detailed below. In addition, each winning entrant received a prize of US$ 500 and a Winner's Certificate.

The 17 additional essays that were selected as Finalists in the 2024 competition are collected here and each of their authors also received a Finalist's Certificate. These essays range across a wide spectrum of topics related to the 2024 theme, covering energy conversion processes related to solar and other renewable forms of energy, biomass energy, and fuel cells, as well as various approaches, such as green chemistry, CO_2 capture and transformation, and improved energy efficiency, to reducing greenhouse gas (GHG) emissions from energy and agriculture. One of the important points highlighted is that renewable energy is not equivalent to carbon neutral energy, since there is still significant CO_2 output from processes such as manufacturing, installation, and decommission of the equipment and infrastructure necessary for renewable sources and therefore a comprehensive, system-based life-cycle approach is essential in assessing the net effect of any new process. Likewise, adoption of the circular economy is not a guarantee of sustainability, although it can help to conserve supplies of strategic materials such as critical minerals and also help reduce the production of waste, including from plastics, by enabling return and recycling.

The essayists gave attention to the need for sustainable, large-scale energy storage approaches, for example discussing the advantages and problems of Li-ion batteries, and also addressing the challenge of replacing fossil fuels in mobile situations such as transport, reviewing the merits and challenges of generating, transporting and safely using alternative energy carriers such as gases like hydrogen and ammonia and liquid organic hydrogen carriers like toluene-methylcyclohexane. Approaches to the reduction of emissions of GHGs from industry discussed in the essays include the electrification of high-temperature manufacturing processes using 'green' electricity, replacement of high-temperature manufacturing processes with lower temperature alternatives that release less GHGs either from the energy conversion or by modifying the chemistry of key reaction steps (e.g., in the manufacture of concrete or steel), applications of catalysis and electrochemistry, as well as the use of bio-based methods to source materials from the bio-conversion of lignocellulosic biomass, including from agricultural wastes. In addressing the challenges of reducing GHG emissions from agriculture, the authors discuss the potential benefits of using manure rather than synthetic fertilisers, of employing methane inhibitors as feed supplements, adoption of regenerative agricultural practises such as cover cropping which, among other things, can increase carbon sequestration and productivity while reducing inputs of water and fertilizers; and use of zeolites as fertilizer carriers to reduce losses. Among methods for carbon capture and storage or utilization, methods cited include the fixing of carbon as diamonds; the trapping of CO_2 permanently or reversibly in diverse solid and liquid absorbents; the use of catalysts and photochemical and electrochemical methods to transform GHGs like CO_2 and CH_4 into harmless or high-value-added products; and changing the absorptive capacity of the oceans through chemical means.

Throughout the essays, the writers show awareness of the importance of support from society and policy-makers for decarbonization of the energy sector and reduction of GHG and other environmentally harmful emissions from the manufacturing and agriculture sectors. They highlight that this support needs to be generated by engagement of scientists and must come in many forms, from prioritisation of lifestyle changes at personal and community to national levels to strengthening laws, monitoring and regulatory systems, implementing taxation levers, and financing and subsidising moves towards cleaner processes and incentivising research and development in green technologies.

Among the 24 high-scoring essays selected for the final round, it was impressive to see that six were aged under 18 on the closing date of 31 March 2024, with the two youngest being aged 16. One of these under-18s emerged as a Regional Winner (Yana Walia, Middle-East and North Africa) and her essay can be found in RSC Sustainability (https://doi.org/10.1039/D4SU90050B). The essays from the other five are included in this volume of Finalists and are highlighted as 'under-18s'. IOCD will continue to encourage entries from under-18s in line with its strategy to promote engagement by young people in the role of the chemical sciences in sustainability.

We are extremely grateful to the Royal Society of Chemistry for its sponsorship, which helps to cover the costs of operating the competition during its first five years, and for its participation in the competition process and publication of the Regional Winner essays. We are also highly indebted to the dozens of volunteer evaluators from around the world who agreed to assist us in reviewing the entries and selecting the Finalists and Winners. Most of all, we are grateful to the young people around the world who made the effort 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 (www.iocd.org) or by writing to essay@iocd.org.

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Regional Winners

Regional Winner

East Asia and Pacific

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

Amanda M. C. Tolentino

Clean Air Asia, Pasig City, 1605 Philippines

Amanda Tolentino begins her essay by stressing that achieving a net-zero future requires global multisectoral efforts, with the chemical sciences playing an indispensable role through technology, education, and policy. She ranges over the use of renewable energy sources and, meanwhile, the role that emissions capture can play on the route to carbon-free exploitation of energy, as well as the importance of innovations that enable circular production that reduces natural resource consumption and facilitates recycling for added value creation and responsible waste management. She also addresses emissions from agriculture, where activities such as livestock farming, crop residue burning, and the use of nitrogen-based fertilizers are common sources of emissions. Looking beyond the technological aspects, she highlights the importance of integrating sustainable practices and concepts into education curricula to orient the worldview of young scientists, and also the need to influence society and policy-makers to reorient public policy.
Article at: *RSC Sustainability*, 2024, https://doi.org/10.1039/D4SU90046D

Regional Winner

Europe and Central Asia

Chemical sciences: the key to a carbon-neutral future

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Alexandre Jorge notes the important contributions that clean energy technologies such as solar photovoltaics, wind, nuclear, heat pumps, and electric cars, already play in reducing the amount of greenhouse gasses emitted. Photoelectrochemical cells for water splitting have potential to be a large-scale source of hydrogen for use as a clean energy carrier, while more research is required to improve the economics of the technology. The essay discusses the need for large-scale energy storage and highlights advances in smaller and safer nuclear technologies, such as small modular reactors, to provide constant energy flow and also power CO_2 capture and sequestration technologies. Ongoing research seeks innovative solutions to challenges in nuclear waste management, such as by developing glass-ceramic composites, to remove, repurpose and/or stabilize the radioactive compounds. Solutions to GHG emissions linked to agriculture referred to include precision agriculture employing artificial intelligence, nanotechnology, energy-efficient frameworks, and sensor networks, as well as optimizing the management of CH_4 emissions from manure storage and treatment. However, the essay also refers to the need for governments and society as a whole to tackle climate change and environmental degradation by ensuring the effective implementation of the technological possibilities.
Article at: *RSC Sustainability*, 2024, https://doi.org/10.1039/D4SU90047B

Regional Winner

Latin America and the Caribbean

Chemical advances in transforming pollutants into new materialss

Tales da Silva Daitx

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Porto Alegre, Brazil

Tales da Silva Daitx focuses on ways that, alongside reductions in burning fossil fuels, the capture and use of CO_2 can contribute to reducing global warming and also provide a feedstock for the development of new materials. This includes development of materials that can be used in agriculture and can also reduce future emissions associated with agriculture (Figure 1). Examples cited in the essay include biodegradable polymers that can act as agrochemical supports and hydrogels, releasing active compounds in a slow and/or controlled manner and being able to provide moisture to a plant for a prolonged time while reducing dosage and leaching less material that is lost to the plant.
Article at: *RSC Sustainability*, 2024, https://doi.org/10.1039/D4SU90051K

Regional Winner

Middle East and North Africa

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

Yana Walia

Brighton College Abu Dhabi

Yana Walia advocates the reduction of greenhouse gases grounded in the principles of green chemistry. One cited approach involves the capture of CO2 released by industrial processes and its subsequent transformation into methanol using bio-catalysis. Hydrogen production by steam methane reforming is an interesting sector where carbon capture can be of great importance for the development of green hydrogen applications. To follow, Walia pinpoints agriculture, a sector that is both partly responsible for and directly victim of the climate crisis. She focuses on methane emission as a result of manure storage and the digestive process of ruminant animals. As she points out, working on feed composition and quality can reduce the level of methane, but this has a cost that farmers in low- and middle-income countries often cannot afford. An alternative, promising strategy consists in feed additives that specifically work on the enzyme responsible for methane release by the ruminant.
Article at: *RSC Sustainability*, 2024, https://doi.org/10.1039/D4SU90050B

Regional Winner

North America

Atoms and Photons. How chemical sciences can catalyse the development of sustainable solutions powered by light

Govind Nanda

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Govind Nanda focuses his essay on diverse manipulations of light, aiming at obtaining clean energy from the sun, improving the energy efficiency of buildings and reaching other decarbonization objectives. In the energy sector, he outlines the merits of silicon-perovskite tandem panels for photovoltaics and describes the promise of low-emissivity materials and smart windows based of electrochromic materials for thermal insulation. At the same time, Nanda recognises that these high-tech devices exert a pressure on the supply of precious metals and will raise recycling problems at their end-of-life. In the domain of intelligent agriculture, he highlights the use of infrared spectroscopy to monitor the growth of plants and thereby collect information to know precisely when and where irrigation or fertilizers are needed, enabling reductions in their use.
Article at: *RSC Sustainability*, 2024, https://doi.org/10.1039/D4SU90048K

Regional Winner

South Asia

Chemical innovations in nuclear energy: paving the way for a carbon-neutral future

Sarah Geo

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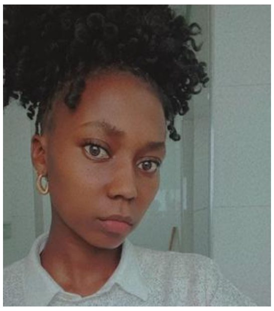
Sarah Geo discusses the advantages of nuclear technology to mitigate the emission of CO2 in the quest for zero emissions. She remarks that, in the nuclear sector, chemistry is involved everywhere, from uranium mining to purification, from enrichment of the fissile component to the production of combustible rods. She adds that the processing of spent fuel to extract interesting isotopes involves complex chemical operations. She comments on the worrying problems of nuclear waste, while being confident that scientists will soon or later propose robust solutions for the storage of radioactive elements over very long periods. She continues with a few applications of radioactivity that increases the sustainability of different activity sectors. An example she takes from agriculture is the sterilization of insect pests by gamma ray irradiation and their dispersion in some regions of the world offering the possibility to reduce the need for pesticides. Another illustration she cites is the use of ionizing radiations for the sterilization of medical instruments or the treatment of medical waste without heat and, therefore, with less energy consumption.
Article at: *RSC Sustainability*, 2024, https://doi.org/10.1039/D4SU90045F



Regional Winner

Sub-Saharan Africa

Utilizing advancements in chemical sciences for decarbonization: a pathway to sustainable emission and energy reduction

Faith M. Johnson

Department of Chemistry, Jomo Kenyatta University of Agriculture and Technology, Juja, Kenya.

Faith Johnson reviews several important routes leading to decarbonization of industrial processes and energy consumption. She starts with green chemistry being a highly desirable alternative to traditional chemical processes that most often are energy-intensive and environmentally damaging. She takes bio-based polymer manufacturing as a convincing example for which different green production routes exist. She continues with transition-metal catalysis employed in fuel-cell technology for carbon-free production of electricity. She cites more complex catalysts showing a high potential for carbon capture and utilization (CCU), emphasizes the important role of chemical sciences in developing new CCU processes and cites different examples of how the captured CO2 can be transformed into useful minerals or chemicals. She closes with energy conversion and storage, such as through solar energy trapping and green hydrogen production, and describes recent research efforts towards alternatives to lithium-based batteries.
Article at: *RSC Sustainability*, 2024, https://doi.org/10.1039/d4su90049a

Finalists

Under-18 Finalist

Solar energy, the silicon market, and the need to revise the manufacture of minerals

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Taking into consideration the difference between sustainable and renewable energy with the chemical science backing it up, solar energy stands as one of the best options to help decarbonize our environment. Sustainable energy can only be qualified as one that is obtained ethically, prepared efficiently, and distributed adequately.[1] In the course of talking about climate change and its relation with ethical sources of energy, the terms sustainability and renewable are often used interchangeably.[2] Although the two terms are interrelated, they are quite different from one another. Renewable energy is focused solely on the source of energy while sustainable energy takes into consideration both the source and the way it is produced and used. Corporate sourcing for sustainable energy takes into account reducing the carbon footprint and the economic aspect in the society.[3]

Solar energy is both renewable and sustainable because it is available everywhere in the world and can be sourced directly. Solar energy works on the principle of converting the energy produced from the sun to heat and electricity. The chemistry behind solar energy is the principle of the photoelectric effect; this is simply an occurrence that happens when electrically charged particles are released when a substance absorbs electrical radiation. This radiation can be infrared, visible or all those that fall on the electromagnetic spectrum.[4]

Photovoltaic cells are the primary materials that allow us to gain energy from the sun. A photovoltaic cell makes use of semiconductors such as silicon to produce electricity from sunlight. A photovoltaic cell is also called a solar cell. The semiconductor is of two types, the p-type silicon which is produced from a combination of elements with one less valence electron than silicon; examples are boron and gallium.[5] The presence of one less electron makes it possible to establish bonds with the surrounding silicon atoms to form a hole. On the other hand, the n-type silicon combines with elements with an extra valence electron allowing it to form a link with the atoms next to silicon; this link is unrestricted inside the silicon structure. The sheets of the p-type and n-type silicon sheets are placed in a layered format to form a solar cell. There is an excess of electrons in the n-sheet while there is an excess of protons due to vacancies. In the surrounding area when the two layers meet, electrons move from the n-type layer to the p-type layer to form a place called depletion zone. The presence of oppositely charged ions creates an internal electric field preventing the n-type layer from filling the hole into the p-type layer.[6] When sunlight strikes a solar cell, electrons in the silicon are expelled, forming "holes. When this happens in an electric field, electrons are moved to the n-type layer and holes to the p-type layer. If you connect the n-type and p-type layers with a metallic wire, electrons will go from the n-type layer to the p-type layer, passing the depletion zone, and then returning to the n-type layer via the external wire, resulting in an electrical flow.[6] Figure 1 shows the different components that make up a solar panel.

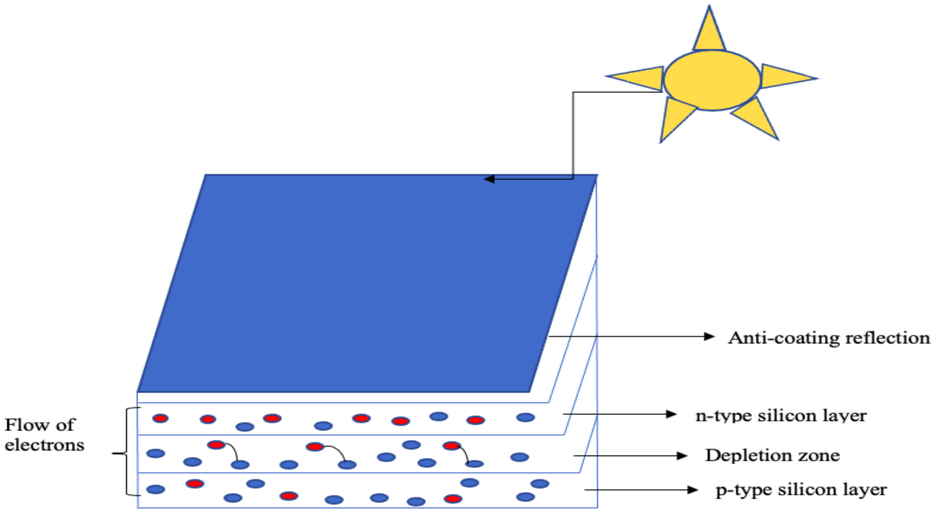

Figure 1: Layers of a solar panel.

Silicon is among the most abundant elements found on the earth's crust; though it exists naturally in the form of silica sand and is often sourced from mining by dredging or on open pits. To be able to obtain silicon from silica, it has to go through a reduction process to remove the oxygen from the ore.[7] The problem that arises is the use of carbon as a reducing agent to form CO (carbon monoxide).

The equation goes as follows:

$$SiO_2 + 2C \rightarrow Si + 2CO$$

As sustainable as solar panels are, the process involved should be revised until the goal of complete decarbonization is reached. As of 2019, the range of producing metallurgical grade silicon has a carbon footprint of about 5.5 – 6.0 t CO_2e/t Si. While it's difficult to streamline the carbon emissions created only by solar panels using silicon, the average carbon footprint by KWh is given as 10.5 – 12 kWh/kg Si as of 2019. [7] Clear comparison of emissions using different sources is as shown in Table 1.[8]

Table 1.0: Carbon emissions for different electricity types

ELECTRICITY TYPE	Coal	Natural gas	Biomass	Solar	Geothermal	Nuclear
Kg/kWh	0.82	0.49	0.23	0.041	0.038	0.012

After evaluating the existing consensus on solar panels, the issues related to silicon manufacture, and why we need to solve them, several nations have already implemented measures to limit carbon emissions from this particular sector.[9] Norway is currently Europe's top producer of aluminium and silicon, and as a result, it urgently has to reduce its emissions to meet a concrete objective. The Norwegian University of Science and Technology discovered a solution to reduce carbon dioxide emissions while reducing silica using a technology known as SisAl. To generate pure silicon, silica or quartz must interact with a reducing agent to eliminate oxygen.[9] Conventionally, carbon functions as the reducing agent but with the use of SisAl by NTNU, aluminium will be implemented instead to eliminate carbon emissions. SisAl's method is exothermic, which releases energy, whereas the traditional process is endothermic, requiring more energy to respond. Normally, 85-92 percent of silica is used up, but adoption of the new procedure uses up to 97-99 percent of silica.[10]

The utilization of solar energy to supersede fossil fuels is already steps ahead in decreasing the global carbon footprint; nonetheless, certain aspects need to be re-examined such as the methodology used to manufacture solar cells, the primary component used to create solar energy.[11] The commercialization of the redesigned SisAl would make solar energy substantially more economically viable, culminating in a considerably greener environment and significantly decarbonizing our planet.

Statement on use of AI

No AI technology was used to prepare the essay.

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Under-18 Finalist

Chemistry's bold solutions for a shining planet

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Greenhouse gas (GHG) emissions pose an imminent danger to our world. These consist of CO_2, CH_4, N_2O and CFCs which cause global warming and the destruction of the ozone layer. The chemical sciences can reduce such emissions on a global scale without relying on individual, uncertain human action. Energy 'decarbonisation' can be achieved through the use of bioenergy and fuel cells. Furthermore, science can reduce the generation of GHGs in agricultural processes (e.g., fertilisation) and large-scale manufacturing processes (e.g. cement-making). Lastly, carbon capturing methods can prevent the release of CO_2 into the atmosphere. In this essay I will highlight the importance of a scientific approach, intersected with society and policy aspects, to reducing GHG emissions.

Chemistry can contribute to 'decarbonising' energy conversion through bioenergy. Energy obtained from biologically-derived material is the biggest global source of renewable energy, providing about 10% of all our energy needs.[1] This type of energy relies on biomass such as sugarcane and maize (or anything biodegradable). Different types of biomass can yield different types of biofuels. For example, fat molecules generate biodiesel through transesterification, whereas sugar molecules can be converted into ethanol through a combination of anaerobic microbial respiration and chemical processing. Within the biosphere carbon cycle, bioenergy is carbon neutral as the carbon released during the biofuel combustion has previously been sequestered from the atmosphere and will be sequestered again as plants regrow.[1] Moreover, biofuel can be supplied without significant changes to existing fuel supply and storage infrastructure. For instance, in Brazil, most cars use either ethanol derived from biomass or gasoline blended with 20% to 25% ethanol.[1] However, depending on the type of feedstock used, biofuel may have significant drawbacks like indirect land use change (deforestation) and competition with food production.[2] This can be regulated: the Dutch government has restricted where biomass can be grown for biofuel (e.g., no areas with high biodiversity).[3] Therefore, biofuels are effective in 'decarbonising' energy conversion because they are easily implemented and they produce net zero CO_2 during combustion.

Another way in which chemistry can contribute to 'decarbonising' energy conversion is through fuel cells. Fuel cells are electrochemical converters; transforming hydrogen and oxygen directly into electricity with only water as the emission product.[4] This process permits the production of electrical energy with high efficiency through a non-combustion, electrochemical process, without the emission of CO_2. Many countries are exploring the use of fuel cells as a method of storage for renewable energy sources such as solar and wind energy.[4] The first version of a fuel cell was invented by William R. Grove, an amateur electrochemist. Grove used two platinum electrodes dipped into an electrolyte to generate an electric current in an external circuit. The first practical hydrogen-oxygen fuel cell was developed as a way to provide electrical power for the Apollo moon mission in 1969.[4] Even though fuel cells are dependent on a constant supply of hydrogen as a fuel, this can be supplied through the electrolysis of water (which produces a very pure form of hydrogen).[5,6] These fuel cells can be implemented in fuel cell electric vehicles (FCEV). The components of these vehicles are being produced in Germany, where legislation regarding the social risks of producing FCEVs has already been implemented (with the European Commission soon to follow with international policies).[7] Therefore, fuel cells offer a highly reliable, carbon-free method of producing energy by being independent of the prevailing conditions of the wind or the sun.

The main GHGs being emitted by agricultural processes are CH_4, N_2O and CO_2.[8] CH_4 and N_2O come from the decomposition of livestock manure under anaerobic conditions (poor manure management).[9] N_2O can also come from the use of synthetic N fertilisers.[10] While manure can be used to make aforementioned biofuel, a better, two-for-one solution would be using manure to fertilise soil. A 25-year fertilisation experiment carried out in Southern China shows that compared to synthetic fertiliser treatments, manure application strongly and positively affected the relative crop yield by increasing soil organic carbon storage, soil nutrients, and soil pH.[11] Another study by Zijian He *et al.* provides data showing that organic fertiliser made out of manure is not only better at fertilising soil but also decreases GHG emissions.[12] Their global meta-analysis indicates that organic fertilisers replacing chemical fertilisers significantly decreased N_2O emissions, but increased global warming potential (GWP) by enhancing CH_4 and CO_2 emissions.[12] However, the optimisation of fertiliser components (carbon and nitrogen) influencing GWP and GHG give a more favourable choice for GHGs reduction.[12] According to He's simulation on paddy fields and dryland, balancing carbon and nitrogen in the organic fertiliser showed that using the optimised organic fertiliser reduced overall GHG emissions.[12] Therefore, chemistry can be used to further explore the ratio of carbon and nitrogen in organic fertilisers in order to minimise the emission of CH_4 and N_2O as much as possible. Thus, using manure organic fertilisers would not only have a positive impact on GHG emissions but also increase crop yield which would contribute to a decrease in world hunger.

The main GHGs being emitted by large-scale manufacturing are N_2O, CO_2 and perfluorocarbons.[13] Within the broader manufacturing sector, industries with high temperature processes produce the largest share of GHG emissions by burning fossil fuels (thereby emitting CO_2). High temperature processes are used for manufacturing cement, iron and steel.[14] Chemical sciences can be used to further innovate the electrification of high temperature processes. Industrial electrification is the replacement of fossil (oil, gas and coal) powered processes with processes powered by green electricity or green molecules. Green electrons are electrons made using renewable resources (e.g., wind and sun).[15] Green molecules are molecules that have been made using green electrons (e.g., green hydrogen).[15] To make green hydrogen, green electrons are run through water, splitting it into hydrogen gas and oxygen. This green hydrogen can be used as an alternative to fossil fuels for the steel industry whilst green electrons can be used for electricity-requiring processes in manufacturing. Furthermore, by turning green electrons into green molecules, energy can be stored cheaply and shipped or piped easily. Green molecules have been successfully implemented in Denmark which now meets 25% of national gas demand with green molecules and has a path to get to 100% green molecules in 2034.[16] Therefore, industrial electrification would prevent the generation of some GHGs in manufacturing (and may even make some industries carbon-negative).

A not-so-conventional method of preventing the release of CO_2 into the atmosphere is by making diamonds. Aether Diamonds, founded by Ryan Shearman and Daniel Wojno, was the first company to use atmospheric carbon to create its sustainable diamonds. The company works with Climeworks, a Zurich-based company that extracts CO_2 from the atmosphere using waste heat from a small town's incinerator.[17] According to Shearman, the CO_2 is first converted into methane and then sent to a reactor, where pressure and heat fuelled by renewable energy convert it into diamonds through chemical vapour deposition.[18] This process is incredibly efficient in converting a harmful gas into an invaluable product: 20 metric tons of CO_2 are taken out of the atmosphere per carat produced.[18] Instead of using the CO_2 captured by Climeworks, the diamond company could use CO_2 emitted by agricultural and manufacturing processes. Technology such as carbon capture, utilisation and storage (CCUS) captures targeted CO_2 emissions from sources such as coal-fired power plants and stores it so that it will not enter the atmosphere.[19] Further, chemistry could contribute to this solution by working on technology that can capture CH_4 emitted by the enteric fermentation of cattle that can be directly put under pressure and heat to make the desired diamonds.[20] Even though this solution would repurpose a lot of CO_2, carbon capture is the most expensive approach to carbon removal: 15-25$/t CO_2 for industrial processes producing "pure" CO_2 streams to 40-120$/t CO_2 for processes with "dilute" gas streams (e.g. cement production). However, governments are already heavily investing in CCUS as it is currently the least-cost or only practical option for deep emission reductions.[21] For instance, despite the Covid−19 crisis, in 2020 governments and industry committed more than 4.5$ billion to CCUS.[21] Thus, combining CCUS with diamond technology would widely benefit environmental efforts whilst promoting socially responsible consumerism.

Overall, the chemical sciences lie at the core of the solutions to reducing GHG emissions. Energy 'decarbonisation' can be realised through the use of biofuels and fuel cells. The release of GHGs from agricultural and large-scale manufacturing processes can be combated with the use of organic fertilisers and green molecules. Finally, aimed carbon capture can be used to prevent the release of CO_2 into the atmosphere. These few contributions picked from a myriad of solutions have been successfully implemented in many countries. While chemistry is at the core of these solutions, governments and society are the components that must urge companies to pivot from wealth to planet health.

Statement on use of AI

No Al technology was used to prepare the essay.

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Under-18 Finalist

Can the chemical sciences improve photovoltaic panels to meet global energy demands?

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Introduction

The efficiency of solar cells poses a large problem worldwide. Entire fields in the UK are taken up by solar panels, decreasing the agricultural land available for a growing population. If the efficiency of solar panels is increased, this could decrease the land use for solar farms, while forming a larger and more reliable output of energy, which does not produce any carbon directly. The efficiency of solar panels has been an ongoing problem, with the average efficiency of a photovoltaic panel being 17-20%.[1] Generally, a method of generating energy is said to be sufficiently efficient to supply a market if its power conversion efficiency is over 80%. Although solar panels have an efficiency well below this threshold, they account for a large proportion of energy production: in the UK, this can be up to ¼ of the total energy produced, depending on factors such as light intensity and temperature. Therefore, increasing the efficiency of solar panels will increase energy production on a large scale, feasibly meeting the majority of energy demands on a bright day.

While manufacturing solar panels produces carbon dioxide, a greenhouse gas which contributes to global warming, organic solar cells have been shown to have very low degradation rates, producing energy at over 80% of its initial efficiency value for 27,000 years.[2] This will decrease the number of solar panels manufactured per year, decreasing carbon emissions. Furthermore, the use of organic components decreases the demand for inorganic semiconductors, decreasing the severity of the current semiconductor shortage, which affects manufacturing worldwide. This shortage arose from a rise in demand during the Covid-19 pandemic, and although the severity of this shortage is decreasing, it remains a concern.

Although both processes are similar, photosynthesis maintains the higher efficiency than photovoltaic cells. This should not be the case, as the major chromophore in plants is chlorophyll, which being green, can absorb fewer wavelengths of light than inorganic solar panels. So how is photosynthesis so efficient? Although there are many theories behind this, the most likely explanation is that the vibrations of the chlorophyll molecules are finely tuned, to correspond to the ~1.8 eV energy gap in the chlorophyll excitons.[3] This results in coupling between the excitons and the fixed chlorophyll molecules. The vibrations are also manipulated so that the highest energy excitons are further away from the reaction centre, allowing the exciton to travel down the resulting energy gradient at femtosecond speeds.[4] This is done by dissipating excess thermal energy into a molecular 'bath'.[5] In this way, the open nature of a biological system does not decrease its efficiency: instead, the plants utilise their interaction with the environment to streamline photosynthesis, instead of being disadvantaged by decoherence. Without this interaction, it would not be possible for excitons to reach the photosynthetic reaction centre before they decay, which occurs on a picosecond timescale.

Photovoltaic panels harvest light in a similar way: photons are absorbed to form excitons, which are then separated into the electron and hole, creating a current as the electrons flow through the conduction band of an electron accepting material, such as tin oxide. However, this process is on average only 15-22% efficient.[6] Plants make use of specialised structures called antennae, which work to increase the surface area of the plant, absorbing more photons. These structures also contain the chlorophyll molecules with higher energy, so that more wavelengths of light are sufficient to excite the molecules and produce an exciton. Imitating these structures could allow the solar panels to absorb more photons, increasing efficiency and power output. Organic solar cells have been modified to use this 'antenna effect'. By using a range of organic dyes, a wide range of electromagnetic radiation can be absorbed by these antennae, and through using a sensitiser at the base of each antenna, with a HOMO-LUMO range lower than the antennae, the energy gradient found in plants is recreated. This has been shown to marginally increase the efficiency of solar cells.[6] By mimicking more aspects of photosynthesis, it is therefore possible to increase the efficiency of organic solar cells, making them a viable option for electricity generation.

However, the thermal 'bath' in the chloroplasts contributes the most to the efficiency of photosynthesis. In the cases of both photosynthesis and PV cells, energy efficiency decreases with heat causing the power output of PV panels to decrease significantly in heat waves.[7] As global warming increases, heat waves have become more frequent and more severe.[8] The increased thermal energy could decouple the excitons from the vibrations of the light-harvesting molecules, making the energy gaps different. As shown by this simulation,[9] the interactions between light-harvesting molecules and their surroundings dictate the speed of transfer of excitonic excitations, showing the importance of the surrounding molecular bath. In solar panels, heat brings another problem: while excitons are not affected by resistance, the increased vibrations of the molecules increase resistance for the separated electrons. Both effects of increased heat decrease the efficiency and power output of solar panels. This means that in heat waves, when light intensity is high, the power output of solar panels is severely dampened. By keeping the solar panels at their optimum temperature, the increased light intensity which we experience with increased temperatures can be utilised. Various methods have been employed to decrease the thermal energy of the solar panels, such as using water cooling systems, and thermal pipes.

Although water cooling systems do increase efficiency, a method which decreases water consumption would be ideal. Apart from carbon dioxide production, many methods of electricity generation use vast volumes of water to cool their systems, such as nuclear power plants. A method of electricity production which cools itself passively, without requiring a constant influx of water would be more environmentally friendly, as well as requiring lower maintenance costs. Solar panels could make use of reversible endothermic reactions of salts and water to cool when a specific temperature is reached. For example, a recent study explored the use of the reversible endothermic reaction between ammonium nitrate and water.[10] The photovoltaic cells used were coated with water-saturated zeolite 13X, which released its water as the temperature of the panel rises to 60 degrees (Figure 1). This causes an immediate latent cooling effect, as well as an increased cooling effect when the solute is dissolved in an endothermic reaction. This system resets at night, and has the ability to reduce temperature by 15.1 degrees. Using a reversible passive system such as this presents a sustainable solution to the decreased efficiency of solar panels with heat, allowing solar panels to be the main source of electrical energy during heat waves, when both light intensity and temperatures are high.

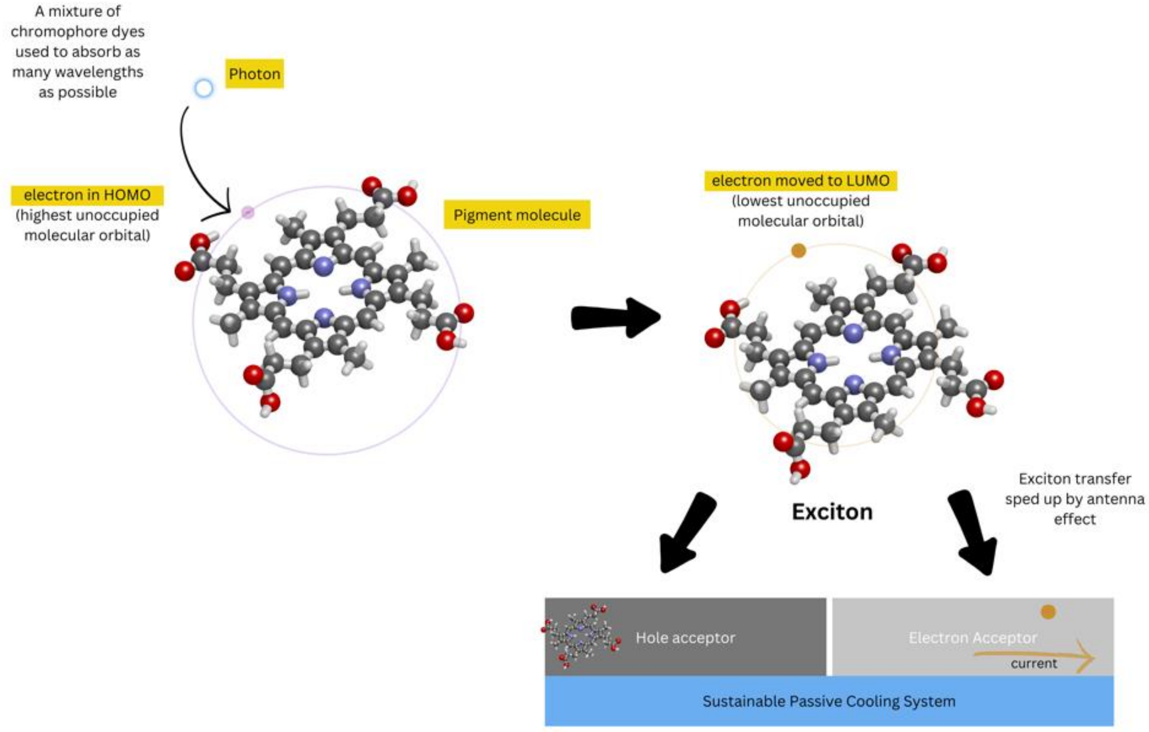

Figure 1 Schematic diagram

Finally, the largest problem with many renewable sources of energy is their fluctuating reliability. Light intensity varies massively with cloud cover, and so the energy production by solar panels is unreliable, causing fossil fuels to be combusted to make up the difference between energy production and demand. If the energy produced by solar cells during periods of high light intensity can be stored, then the use of fossil fuels will decrease accordingly. Excess energy generated during heat waves, which are becoming more frequent with climate change, could also be stored for darker months of the year, when countries such as the UK become more dependent on fossil fuels. In photosynthesis, energy is stored in the bonds of the carbohydrates produced: perhaps the excess energy from solar cells could be used to form larger organic molecules in a similar way, which can then be hydrolysed by enzymes or combusted to release the thermal energy stored. Although combustion would produce CO_2, this would be from a renewable source, reducing the damaging effects of deforestation, drilling, and mining.

In conclusion, there have been many recent advancements to photovoltaic cells. Organic photovoltaic cells have increased in efficiency over recent years, and are now able to match inorganic commercial cells.[11] This efficiency could be further increased by methods which mimic photosynthetic processes, such as using multiple photoreceptive dyes, advancing cooling systems which replicate the thermal 'bath' used by plants, and finally replicating the antenna effect, summarised in the diagram above. Solar panels can also be improved to have a longer lifetime, decreasing the carbon emissions produced by their manufacture. The current lifetime of a photovoltaic cell is around 25 years: therefore, every solar panel is expected to be replaced by 2050, a key date for global climate goals. If all current photovoltaic cells are replaced by these more efficient and sustainable models, global electricity generation can be expected to be significantly more dependent on solar power. If photosynthesis is 99% efficient, this should be the target aimed for by our photovoltaic cells.

Statement on use of AI

No Al technology was used to prepare the essay.

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Finalist

Decarbonize and energize: how chemistry saves planet

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Introduction

The unprecedented global disturbance of COVID-19 presented diverse challenges, not only to human society but also to the natural environment and global economy. It caused a significant 5.1% decrease in global CO_2 emissions, offering a glimpse into the potential impact of reduced human activity on greenhouse gas emissions.[1] However, this positive trend proved short-lived, as emissions rebounded, surpassing 2020 levels by over 2.0 Gt in 2021. This marked the largest ever year-on-year increase in energy-related CO_2 emissions.[1] Beyond CO_2, human intervention has also introduced additional greenhouse gases such as CH_4, N_2O, hydrofluorocarbons, ozone, and sulfur hexafluoride into the atmosphere, which are far more dangerous, with global warming potential of CH_4 and N_2O being 21 and 310 times greater than CO_2, collectively contributing to environmental challenges.[2,3]

What makes greenhouse gas emissions worrisome, and what exactly causes the greenhouse effect?

Greenhouse gases (GHG) pose a significant concern due to their role in intensifying the greenhouse effect, a natural phenomenon vital for regulating Earth's temperature. However, an excess of these gases disrupts the delicate balance, leading to global warming. The consequences of this global warming are far-reaching, resulting in extreme weather phenomena such as prolonged heatwaves, intensified droughts, torrential rains, and severe storms.[4] These events pose substantial threats to ecosystems, human livelihoods, and food security worldwide. Moreover, the impacts of climate change extend beyond immediate weather events. Rising temperatures contribute to the melting of polar ice caps and glaciers, leading to sea level rise, which threatens coastal communities and habitats. Additionally, shifts in precipitation patterns can disrupt agricultural systems, affecting food production and increasing global food insecurity.[2,4,5]

In what ways do the large-scale and agricultural sectors contribute to emissions?

Agricultural activities are significant contributors to greenhouse gas emissions, particularly during the primary production stage.[2,5] In countries like India, where agriculture is vital for livelihoods and the economy, understanding these emissions is crucial. Various agricultural practices, such as using farm machinery, disturbing soil, managing residues, irrigation, and applying inputs like fertilizers, aim to improve yields but they can also harm the soil health and lead to emissions. Manure decomposition releases gases like CO_2, CH_4, N_2O, and CO.[2] In cereal cultivation, soil microbes produce methane, especially in rice paddies.[5] Microbial processes like nitrification and denitrification also release N_2O. Additionally, the energy-intensive production of chemical fertilizers adds to emissions.[2,5] Understanding these complexities is crucial for developing sustainable agricultural practices that minimize GHG emissions while ensuring food security and livelihoods.

Contribution to GHG by large scale industries

The ongoing global industrialization and reliance on non-renewable energy sources are escalating greenhouse gas emissions. CO_2 emissions primarily result from burning fossil fuels, with the road transportation sector being a major contributor.[6] Additionally, in sectors like chemicals, the production of essential substances such as olefins for plastics and ammonia for fertilizers heavily depends on fossil fuels, leading to significant environmental harm. Plastic production, a major component of the chemical industry, predominantly relies on fossil fuels, especially in processes like steam refining to create ethylene, a crucial precursor for plastics, textiles, and synthetic rubbers.[6] Nearly all single-use plastics, around 98%, originate from fossil fuels. Throughout the lifecycle of plastics, from extraction to manufacturing, and eventual disposal or incineration, greenhouse gases, particularly carbon dioxide, are emitted at various stages. This continuous emission further worsens climate change and environmental pollution. Industries also contribute to greenhouse gas emissions through the production of chemicals that possess potent greenhouse properties themselves.

What are the measures in chemistry that can be taken to address these challenges?

Addressing the challenges outlined above requires a fundamental shift in the chemical sector towards more sustainable practices, reducing its dependence on fossil fuels (**Figure 1**). To tackle the alarming emissions into the atmosphere, extensive research is focused on capturing CO_2 emissions from various point sources. Carbon capture, utilization, and storage (CCUS) technologies aim to capture CO_2 emissions and either store them underground or convert them into valuable products such as fuels and chemicals.[3] Over the last few years, a lot of research has been dedicated to designing materials that are capable of CO_2 capture. Some of the well-studied materials include adsorbent based on amine (Polyethyleneimine), silica (MCM-41, SBA-15), carbon (CNTs, fullerenes), MOFs, polymers, zeolites, alumina. [3,4]

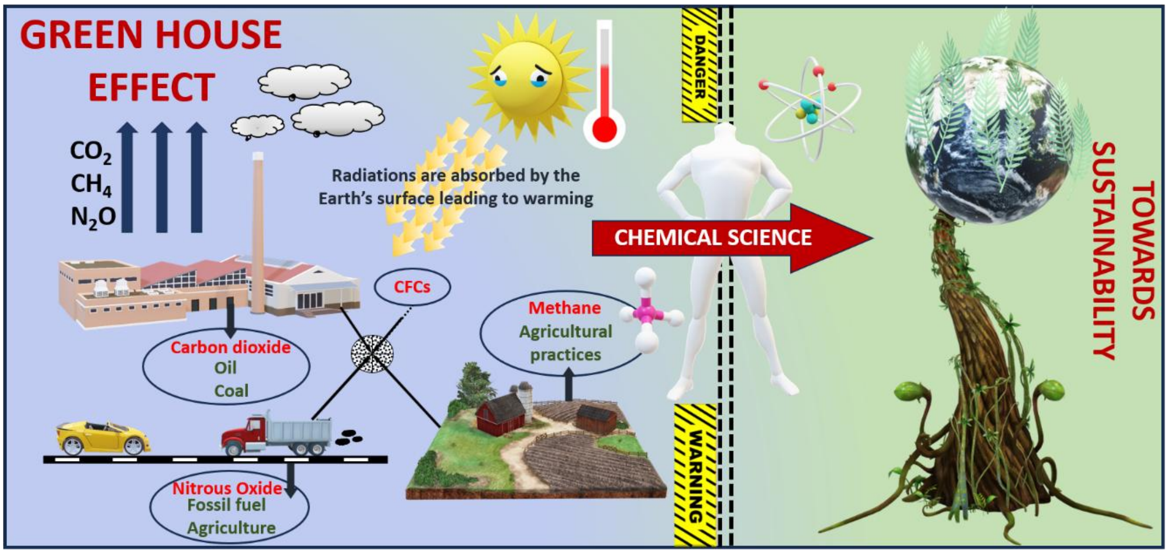

Figure 1: Role of chemical sciences towards sustainability

Targeted C-H and CO_2 activation techniques[7,8] offer avenues for addressing GHG emissions in various ways: By employing C-H activation techniques, methane (CH_4), a potent greenhouse gas, can be converted into more useful and less harmful products like methanol or ethylene. Selectively breaking C-H bonds in methane enables the capture and utilization of methane emissions from sources such as natural gas wells, landfills, and livestock operations, thereby controlling its release into the atmosphere. This approach considers sigma and agostic interactions, with pioneering work on methane sigma complexes, led by Brookhart and colleagues, marking a crucial milestone. Subsequently, numerous examples of sigma interactions have been reported, with various 3d metals such as Co, Mn, Fe, Ni, and carbenes showing promise in this field.[8–10] CO_2 activation, source of C1 feedstock for formic acid and methanol, has been studied using the transition metal hydride complexes.[7,11]

There have been numerous studies highlighting the efficacy of utilizing photocatalysts based on metal oxides such as MgO, ZnO, and TiO_2 to convert CH_4 into CO_2.[12] This process is significant as the global warming potential of CO_2 is over 10 times lower than that of methane. Additionally, these catalysts have demonstrated the ability to convert various chlorofluorocarbons (CFCs) and hydrofluorocarbons (HFCs) into CO_2, effectively reducing their potency as greenhouse gases. Moreover, the effect of N_2O can be lessened by employing catalysts containing transition metals like Ag, Ti, Cr, and Cu, which are supported on diverse substrates such as zeolite and TiO_2. These catalysts facilitate the reduction of nitrous oxide to harmless N_2 and O_2.[12]

Investing in carbon-free technology and infrastructure is crucial for both the chemical and transportation industries. While carbon capture, utilization, and storage (CCUS) technologies show promising efficiency, they primarily focus on controlling CO_2 emissions from stationary fossil fuel plants. However, when considering the automobile sector, alternative approaches need to be explored. Transitioning from fossil fuels to low and zero-carbon energy sources, such as natural gas and renewable energy, is crucial for reducing CO_2 emissions at their source. Hydrogen, with a high gravimetric energy density (33.0 kWh/kg),[13] thrice more than that present in natural gas, is a green and an environment friendly alternate. Chemical science offers potential solutions for hydrogen storage and handling challenges, including the development of liquid organic hydrogen carriers (LOHCs) like toluene-methylcyclohexane, initially proposed by Chiyoda in collaboration with Mitsubishi

Corporation, enabling safe transportation and storage of hydrogen. The LOHC approach involves loading hydrogen onto carrier molecules, Once loaded, the hydrogenated compound can be safely transported and stored until needed. Upon demand, the stored hydrogen is released through a catalytic dehydrogenation reaction, often requiring elevated temperatures. Investigations on hydrocarbons, such as cycloalkanes, N-heterocycles, formic acid, and methanol have been carried out. These compounds offer a range of advantages, including a substantial hydrogen capacity (5-8 wt%), reversibility, environment friendliness (by products of H_2 combustion are energy and water) and compatibility with existing gasoline infrastructure.[14–17] Realizing the full potential of LOHCs necessitates systems with favourable thermodynamics and rapid kinetics, crucial for successful commercial deployment.

In agriculture, the prevalent monoculture practices often lead to excessive use of chemical fertilizers, resulting in soil degradation and significant nitrous oxide emissions. To address this, farmers are increasingly turning to organic fertilizers and integrated farming systems.[18] Precise fertilizer management techniques, utilizing isotope tracers like ^{15}N and ^{13}C, enable accurate estimation of nutrient uptake by plants and assessment of soil fertility. Increasing ocean alkalinity presents another approach to combatting atmospheric CO_2 levels, requiring a comprehensive understanding of ocean chemistry for effective implementation.[18]

Conclusion

In today's world, the need to meet ever-growing energy needs while safeguarding the environment has reached critical levels. Chemistry emerges as a pivotal force in this endeavour, offering solutions to the challenges of hydrogen storage and handling. Transitioning from fossil fuels to hydrogen and reducing reliance on chemical fertilizers can significantly contribute to building a sustainable economy. As the fundamental science of matter, chemistry holds the key to reshaping the energy needs. By embracing cleaner alternatives like hydrogen, the harmful impact of greenhouse gas emissions can be effectively controlled. Extensive research efforts, ranging from preventing the release of greenhouse gases to remediation strategies for those already present in the atmosphere toward a greener, more sustainable future are already underway.

Statement on use of AI

No Al technology was used to prepare the essay.

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Finalist

Chemical sciences unleashed: decarbonizing the giants of manufacturing

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Nearly all human activities contribute to the release of greenhouse gases, particularly carbon dioxide, which drives climate change.[1] As per available data[2] from 2016, 73.2% of emissions came from the energy sector; 18.4% from agriculture, forestry, and land use; 5.2% from industries (Scope 1 or direct emissions[3]); and 3.2% from waste. To avert reaching a critical threshold where irreversible consequences occur, we must cease emitting these gases into the atmosphere. It is a task spread across all of society.[4]

Given that we reside in a capitalist society, governments worldwide typically aim to enhance individual economic prosperity, a goal achievable without causing harm to the planet. The energy sector (which, as stated above, accounts for about 3/4th of our emissions) serves as an excellent example of it – the world's best solar power schemes currently provide electricity at the lowest cost in history, with the technology proving cheaper than coal and gas in most of the major countries.[5] Countries like China have witnessed record growth in clean energy – China added more solar panels in 2023 than the United States did in its entire history.[6] Analysis indicates that, among other factors, due to the extensive deployment of renewable energy sources, China's net emissions are projected to decrease this year.[7] This year, the capacity of solar and wind energy in China is poised to surpass that of coal.[8] Findings suggest that by 2025, renewables will exceed coal to become the primary source of electricity generation, and by 2028, greater than 42% of global electricity production will stem from renewable sources.[9] Renewable electricity generation capacity worldwide is expanding at an unprecedented rate, thus presenting a real opportunity to achieve the goal set by governments at the 28th meeting of the Conference of the Parties (COP28) to the United Nations Framework Convention on Climate Change of tripling global capacity by 2030.[10] Although we are making strides in decarbonizing our electricity generation methods, as of 2022, electricity only accounted for a 20.4% share of society's overall energy usage.[11] Other forms of energy generation are still very much dependent on fossil fuels – therefore, while we are off to a good start in tackling the major emission-producing sector, there is still much work to be done.

As electricity generated from renewable sources becomes more cost-effective, sub-sectors of energy such as transportation and heating are becoming increasingly feasible candidates for electrification. However, there are still several sub-sectors of energy, like large-scale industrial production of materials, particularly cement[12] and steel[13] – in 2023, 4.1 billion tons of cement[14] and 18.88 billion tons of steel[15] were produced, which are challenging to electrify. In addition to the difficulties in electrifying them, historically, the cement and steel manufacturing industries have been considered tough to decarbonize owing to the Scope 1 emissions linked with existing manufacturing methods.[16] In my view, chemical sciences play a pivotal role in the decarbonization of the aforementioned manufacturing industries, among others.

During Portland cement production, the calcination of limestone (or calcium carbonate, the major raw material required) to calcia (calcium oxide) releases carbon dioxide that most industries just release out in the air.[2,17] Despite utilizing renewable energy in cement production, the emission of carbon dioxide remains unavoidable. Assuming an optimistic scenario where every gram of calcia generated is efficiently utilized as a precursor for cement manufacturing, we are still left with a one-ton carbon dioxide equivalent for every one ton of calcia produced. A modification to the current production process is necessary to prevent the currently unavoidable carbon dioxide emissions, among others – chemical sciences play a fundamental role in facilitating such changes. An example of this can be observed in the establishment of Sublime Systems, a company dedicated to the production of low-carbon cement.[18] Utilizing an electrochemical process, Sublime Systems transforms readily accessible non-carbonate rocks and centuries-old industrial waste into cement at ambient temperature, without releasing carbon dioxide during decomposition.[19] Their method offers two primary advantages: firstly, it eradicates direct carbon dioxide emissions; secondly, as it is viable at ambient temperature, it requires significantly less operational energy. On the contrary, Heidelberg Materials has integrated ground granulated blast furnace slag, a residual material from iron production, as a precursor in cement manufacturing, leading to reduced emissions.[20] Hence, modifications in the production process driven by chemical sciences can effectively reduce both Scope 1 and 2 emissions originating from cement production.

The predominant method of steelmaking typically begins with the conversion of iron oxide into elemental iron, achieved by reducing the former at extremely high temperatures using coal.[21] Similar to traditional cement production, this process inevitably results in the emission of carbon dioxide, even when renewable energy sources are employed. The production of one ton of steel generates approximately 1.4 tons of direct carbon dioxide emissions.[22] A process modification driven by chemical sciences is necessary to mitigate the currently unavoidable carbon dioxide emissions. One possible pathway is replacing the currently used reducing agent: coal. Researchers have already documented the utilization of non-carbon-based reducing agents such as ammonia[23] and hydrogen.[24] Therefore, a chemical sciences-driven modification in the production process can effectively decrease Scope 1 emissions originating from steel production.

In conclusion, addressing greenhouse gas emissions and mitigating climate change require multifaceted approaches across various sectors of society. While decent progress has been made, particularly in the energy sector with the widespread adoption of renewable sources, there remain substantial challenges in decarbonizing manufacturing industries. The large-scale manufacturing industries, known for their significant 'unavoidable' emissions, necessitate innovative solutions rooted in chemical sciences to achieve substantial reductions in environmental footprints. Initiatives such as those undertaken by Sublime Systems and Heidelberg Materials exemplify the potential of chemical sciences in revolutionizing traditional manufacturing processes, offering low-carbon alternatives that significantly diminish environmental impact. Moreover, ongoing research into alternative reducing agents for steelmaking underscores the importance of chemical sciences ensued technological advancements in achieving sustainability goals. As we continue to strive toward a sustainable future, collaboration between policymakers, industries, and academia becomes increasingly crucial. By harnessing the power of chemical sciences and embracing innovative technologies, we can drive meaningful change and pave the way for a more sustainable and environmentally conscious society.

Statement on use of AI

Artificial Intelligence (AI), specifically Grammarly and ChatGPT, was utilized strictly and solely for the purpose of English language editing in certain portions of the work. The assistance provided by AI was strictly limited to improving the readability and language of the text. No content, ideas, data, statistics, or information generated or sourced by AI has been incorporated into this essay.

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Finalist

Decarbonizing the future: leveraging chemistry to combat GHGs emissions

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Introduction

According to the Annual 2023 Global Climate Report,[1] in 2023 global temperatures reached levels unprecedented since records began in 1850. The Report indicates an alarming combined land and ocean average temperature rise of +1.18 °C. We are experiencing the detrimental impacts of climate change on our planet and our lives. These effects encompass alterations in biodiversity and ecosystems, as well as implications for agriculture and food security.[2] For years now, we are in the midst of a profound "shift in thinking" with the goal of reevaluating our relationship with the environment and natural resources for a sustainable future.

The main cause of this long-anticipated catastrophic reality lies in the continuous emission of greenhouse gases (GHGs), particularly carbon dioxide, methane and nitrous oxides, which have increased dramatically due to industrialization and the rising demand for agricultural resources, due to world's growing population.[3] Certainly, much of the GHGs are a consequence of industrial activities, including chemical, petroleum refining, cement and steelmaking, that contribute about 30% of the emissions in the USA.[4] However, the expansion of agricultural areas has led to a notable increase in global annual GHGs emissions, accounting for about 12% of total emissions.

The significant impact of agriculture on GHGs emissions primarily arises from the use of fossil fuels for on-farm energy, the overuse of synthetic nitrogen-based fertilizers, which favour nitrous oxide formation through microbial fermentation, and methane emissions from rice cultivation caused by anaerobic soil conditions, as well as from ruminal digestion, manure management, and crop residue decomposition.[5] Decarbonization is an important driver in decreasing GHGs, particularly carbon dioxide emissions. For example, daily global CO_2 emissions recorded in April 2020 decreased by the 17% reduction compared to 2019's average levels, due to the restrictions on populations imposed in response to the pandemic emergence. On the other hand, pandemic has presented an unprecedented challenge to global economic stability, prompting governments worldwide to endorse measures aimed at mitigating the economic fallout.[6] In this scenario, policy actions for economic recovery could undermine decarbonization efforts by preferring short-term economic gains. In brief, to effectively reduce the carbon footprint of human activities, long-term strategies in energy conversion, industrial manufacturing, agriculture and consumption need to be deployed.

Achieving these goals relies on fostering synergies between society, industry and policy making. Implement mechanisms such as carbon taxes or cap-and-trade systems, would incentivize companies to invest in cleaner technologies, thus promoting carbon-neutral processes. To do this, industries must rely on chemical research, working to develop sustainable and eco-friendly processes, using renewable feedstocks and designing efficient catalytic reactions. In this sense, chemical sciences are guiding policy decisions toward a "green recovery" approach. According to the United Nations Economic Commission for Europe, maximizing the use and interplay of all low- and zero-carbon technologies will reduce the dependence from fossil fuel by 60% in 2050.[7]

Strategies, approaches and processes to limit GHGs emissions from biomass

The development of sustainable technologies, innovations and practices that convert biomass and waste materials into valuable products is essential for a net-zero emissions future. In 2022, biomass accounted for nearly 5% of U.S. total primary energy consumption, both for heating and electricity generation, as well as source of transportation fuels.[8]

Nowadays, advances in catalytic technologies enable the production of a diverse array of bio-based products with improved efficiency and scalability in multiple sectors, including chemicals, fuels, plastics, food, and water treatment.[9]

By leveraging synergies between chemical sciences and agriculture, the transition to bio-based materials and bio-based energy can reduce dependence on fossil fuels and minimize waste and environmental impact. To this end, catalysis has significant potential to advance decarbonization by enabling efficient conversion of biomass into value-added products, such as biofuels, biochemicals, bioplastics and biocomposites. This is extremely important, for example, to decarbonize chemical and plastics industries that significantly contribute to carbon emissions as they rely on fossil fuels as feedstock, and also for the impact of the end-of-life of plastic products, often not biodegradable.[10]

"Drop-in" bio-based fuels (biodiesel, bioethanol, and biomethane) alongside the adoption of renewable energy sources like sunlight, wind and water are amid the alternative energy sources for curbing carbon emissions of agricultural operations.[5] Yet, proper management of crop residues and wastewater within agri-food supply chain, as well as wood and non-wood biomass, is also required for optimizing soil health and mitigating GHGs emissions. All types of lignocellulosic biomass, composed mainly of cellulose, hemicellulose and lignin, are a huge potential source of carbon polymers that can be used as a raw material for the synthesis of different value-added products. The difficulty of fractionating the lignocellulosic components without degrading them into unwanted products during processing has been a challenge. The recent environmental and energy crises has led to a new start of chemical research aimed at developing new green methods for treatment and isolation of the main lignocellulosic components. These include the use of new solvents (organosolv, deep eutectic solvents, supercritical fluids), cold plasma technology, enzymatic treatments, and physical techniques such as acoustic and hydrodynamic cavitation. The aim of these approaches is to avoid the need for costly conventional extraction methods relying on harsh chemicals, high temperature and pressure, large energy consumption and low productivity, that hindered widespread industrial application of lignocellulose as feedstocks for decades.[10]

Cellulose is the most abundant biodegradable polymer, and its derivatives are useful for a variety of purposes, such as food additives, pharmaceuticals and cosmetics, detergents, coatings, eyeglass frames, wastewater treatment, etc. The peculiar aromatic structure of lignin, in its turn, potentially makes it a source of value-added chemicals such as phenols widely used in the polymer industry to make for example polyesters and epoxy resins. Showing the relevance of catalysis to the bioeconomy transition, hydrogenolysis of lignin mediated by the low-cost Raney-Ni catalyst affords said phenols in high yield at low-cost, unlike thermochemical and hydrothermal treatments (pyrolysis, acid hydrolysis, and gasification) that lead to the formation of substantial waste like inorganic salts, besides requiring elevated temperatures.[11]

Agricultural practices such as the overuse of nitrogen- and phosphorus-based fertilizers cause eutrophication.[12] Similarly, the significant contribution of synthetic pesticide use to GHGs emissions is underestimated. In fact, pesticide production emits on average about five-times more GHG per kg than the production of synthetic nitrogen-fertilizers.[13] Production of biopesticides and/or natural fertilizers through greener technologies is emerging as a significant trend in agricultural sustainability.

Among these, hydrodynamic cavitation is a green route to extract bioactive compounds from natural sources. This process preserves thermolabile and unstable compounds being carried out at ambient pressure and temperature using water as only extraction medium. Application of the process to the extraction of hydrolysable tannins from sweet chestnut (*Castanea sativa* Mill) wood recently afforded a powerful biostimulant and biopesticide dubbed "HyTan".[14]

Similarly, applied to orange (*Citrus sinensis*) industrial processing waste microwave-assisted extraction carried out in water only affords orange essential oil.[15] Orange oil is generally comprised of *d*-limonene up to 90% or higher percentage. Limonene is a versatile compound used across diverse industrial fields and in agriculture. The terpene is also the precursor of limonene oxide (LO, 1,2-limonene epoxide) that readily polymerized with CO_2 via an efficient catalytic reaction affords poly(limonene carbonate), a bio-based polycarbonate imparted with superior thermal, mechanical and optical properties when compared to conventional polycarbonates derived from toxic bisphenol-A.[16]

The conventional synthesis of LO using an excess of toxic oxidant needs to be replaced with clean routes preferably using air, O_2 or H_2O_2 as primary oxidant. Showing the potential of today's catalysis innovation, TitaniaSun, a silyl-modified TiO_2 photocatalyst, allows the green and efficient (high-yield and selective) photocatalytic aerobic oxidation of limonene to LO using O_2 as the unique primary oxidant and visible-light as light source.[17] This could pave the way for the large-scale solar synthesis of limonene epoxide and consequently its industrial applicability.

To date, many catalytic technologies for biomass conversion have not reached the commercial level. Often, basic research conducted on a small, lab-scale does not adequately consider industrial applicability, resulting in inventions that are carried out in batch or continuous-flow pressure reactors on mg scale, ignoring industrial aspects. Furthermore, batch reactor studies are not well-suited for evaluating time of stream, a parameter that evaluates the catalyst stability.[18] Prioritizing industrial scalability during the design phase ensures cost prediction, efficiency, and productivity in large-scale production, and allows to expedite the transition from laboratory-scale proof-of-concept to industrial-scale implementation, reducing the time to address the ongoing climate change.

Conclusions

Exploiting chemo- and biocatalytic processes, the bioeconomy enhances the value of waste biomass feedstocks generated in agriculture, thereby achieving sustainability goals and the transition to a low-carbon economy.[19]

The efforts of chemists to develop selective, low-cost and durable catalysts for biomass conversion not impacting the food chain, aim to make the processes more efficient, economical and environmentally friendly. Chemists are guided in these efforts by the main green chemistry principles of the atom economy and efficiency, to maximize the yield of a desired product while minimizing the amount of energy required. Consequently, it is critical to assess whether sustainable processes are economically and technically feasible on industrial scale, since the early phase of research.[20]

Statement on use of AI

No Al technology was used to prepare the essay.

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Finalist

Dealing the dirty work: chemical sciences for decarbonizing agricultural emissions through sustainable manure management

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The Law of Chemical Equilibrium describes the balance between forward and reverse reactions in a chemical system. Simply put, chemicals are like a seesaw where reactions move back and forth until they reach equilibrium. In a way, the same can be said about our planet today. The Earth's resources can be seen as reactants, with human consumption as the forward reaction and its outcomes as the reverse reaction. When human activities result in excessive exploitation and environmental degradation, the equilibrium shifts unfavorably leading to consequences like climate change.

Balance is important in achieving sustainability, but the reality is we are teetering across the edge of global instability while trying to attain the 1.5°C benchmark per the Paris Agreement. Reducing our carbon footprint and emissions has been an uphill battle, especially with the agriculture sector contributing up to 21-37% of total global emissions—approximately 19 billion tons of CO_2-equivalent gas released annually.[1] There is a need to reevaluate our environmental management techniques such that fundamentally address the agriculture industry which has long been a hotpot of human consumption, and consequently, pollutants.

From Figure 1, different aspects of agriculture contribute to these staggering numbers: chemical fertilizer production, cropland management, waste burning, organic manure, and enteric fermentation, just to name a few. Machinery use, land conversion, and waste burning from crop and livestock activities are the largest contributors mainly due to deforestation and land degradation that comes with developing farmlands.[2] Carbon dioxide emitted from land use tops the list of total emissions from livestock systems, followed by N_2O from manure and slurry management, then CH_4 from enteric fermentation of ruminants.[3] However, the continuous intensification and specialization of livestock production also result in increasing quantities of organic waste.

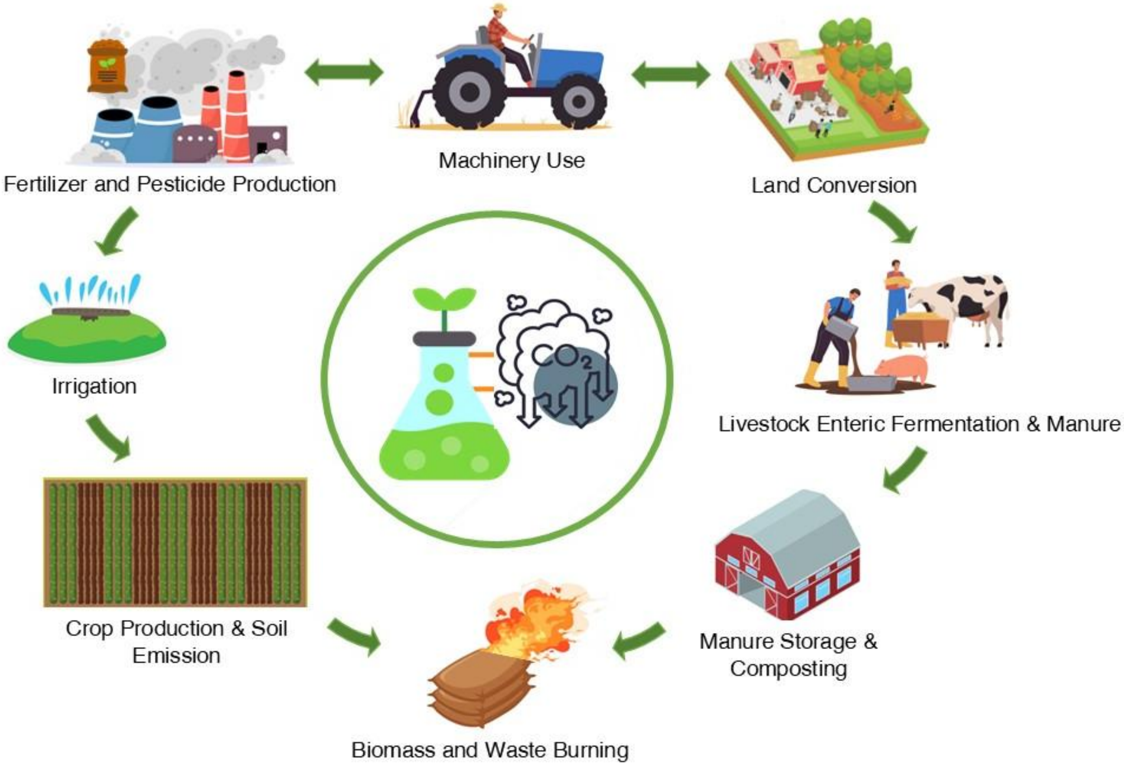

Figure 1. *Major greenhouse gas (GHG) contributors of cropland and livestock agriculture.*[4]

Manure has been overlooked as a significant source of GHGs even with its considerable release of methane from natural storage treatment and nitrous oxide from composting. Recent carbon accounting revealed that 65% of methane emissions were released by manure alone from 2010-2020 in the U.S.[5] While enteric fermentation emissions in East Asia have remained stable, manure management emissions were found to continuously increase up until 2019.[6] More research has been underway to prove this in other continents as well, and from this perspective, addressing manure emissions could have the potential to create the greatest immediate impact on total greenhouse emissions.

The agricultural alchemy

Chemical sciences play a key role in manure management by analyzing the chemical dynamics of organic waste from its origin up to application. Manure contains important nutrients such as nitrogen (N), phosphorus (P), potassium (K), and other secondary nutrients and trace elements. Anaerobic decomposition, ammonia volatilization, nitrification, and denitrification are just a few natural processes in which organic waste produces emissions of carbon, methane, nitrous oxide, and ammonia. On an elemental scale, mineral thresholds in fertilizers are usually gauged in terms of zinc and copper dosages in soil. These minerals and their role in biogeochemical cycles have been tapped for potential implications in fluxing GHGs.

More recently, a promising approach for manure management involves conversion to methane-rich biogas through anaerobic digestion. A variety of processes are involved in anaerobic digestion: hydrolysis, acidogenesis, acetogenesis, methanogenesis, combustion, gasification, and pyrolysis[7]—all of which necessitate understanding at a chemical level. This process of biological degradation offers a way to improve the overall GHG balance through the generation of renewable bioenergy. Methane amelioration using feed additives has also involved carrying out trials with components such as organic acids, fibers, fats, starch, cellulose, etc.[8] Further progress in biochemistry has explored incubating fodder with fungal enzymes to help improve feed quality and reduce GHGs by reducing the activity of pure methanogenic bacteria. [9] Similarly, the conversion of animal waste and crop residue through pyrolysis produces biochars that allow long-term carbon sequestration and reduction of nitrous oxide by reducing nitrogen leaching.[10]

Responding to the bigger problem involves taking a closer look at manure at a fundamental level where chemistry becomes crucial. Research may be capable of testing these theories, but practical application outside funnels and flasks is what imbues these chemistry concepts with greater significance.

From lab to land

The recent strides of chemical sciences in reducing agricultural emissions have yielded significant results in various settings. The usual approach of these models is to assess several types of manure processing in its life cycle from anaerobic digestion, solid-liquid separation, and nutrient recovery.

Waste containing organic compounds can be utilized to generate biogas through anaerobic digestion.[11] A recent case study has proven this in one of the bio gasification systems operating on the Yuge Farm in Kobe, Japan.[12] Curating the substrates has increased biogas production with an electrical energy potential of 2843.20 kWh/year, contrary to the current output of 518.28 kWh/year. The proposed scenario was also able to increase the avoided emissions by more than five times less than usual. This circular economy approach shows how effective manure management not only influences GHG mitigation but also contributes to renewable energy targets.

Smaller-scale interventions have also shown promising outcomes in reducing emissions. With the need to control emissions from the manure storage and treatment phase, the addition of solid-liquid separation and nutrients has also been found to significantly reduce CH_4 emissions from outdoor liquid digestate storage by 87%. On the other hand, a study assessing the gas adsorption properties of porous biochar surfaces was found to improve oxygen diffusion and cut methane release by 84% and other emissions by up to 61-70%.[13] These are just a few examples of how fighting fire with fire can work, wherein chemistry-based interventions combat chemical emissions.

There has also far been more technological advancement in the last decade alone compared to the past century. The marriage of evolutionary algorithms and chemistry has resulted in innovative approaches to analyzing agricultural life cycles. Collaboration between chemists and data scientists brought forth the development of a simulation model for predicting methane and ammonia emissions from commercial pig houses.[14] With programming, a FarmM3 model was made to quantify the degradation of different manure management chains, thereby optimizing waste management strategies in large-scale dairy farms. [15] Additionally in Canada, a dairy farm algorithmic model—DairyCrop-Syst—was used to simulate storage emissions of methane, nitrous oxide, and ammonia to replicate nutrient farm distribution.[16] With the assimilation of chemistry and technology, we can essentially track the creation of emissions based on animal and farm characteristics.

Facing the filth

Mitigating GHG emissions is a multifaceted challenge that represents a system in flux, and achieving equilibrium implies going back and forth with concerted efforts to improve our practices. While systematic selection of manure management practices can provide environmental benefits, accounting for local constraints, economics and farming practices pose significant challenges. Current policies often oversee livestock manure management in agricultural policies as it is categorized as a pollution source and health risk instead of a resource. [17] This results in limited action to enforce proper handling due to inconsistent policies and cost being a roadblock to implementation. Establishing a standardized manure redistribution system has long been hampered by the lack of financial and monitoring mechanisms consequently delaying a more robust manure storage and application infrastructure.[17, 18]

Manure management alone directly addresses at least four Sustainable Development Goals: Clean Water and Sanitation, Responsible Consumption and Production, Life on Land, and from what was highlighted, Climate Action. However, the main bottleneck is the lack of support to advance these agricultural breakthroughs at either a massive or even grassroots scale. Even China, an agriculture powerhouse, has no measures to ensure the incentivization of sustainable manure treatment facilities and technologies such as anaerobic digesters, nutrient recovery units, and liquefaction technologies.[18] Incentives, technical support, environmental regulations, and farmers' education level have been identified as impactful factors for a farmer's choice of manure treatment technology. [19] A direct micro-approach to target different farm archetypes and proper stakeholder engagement is therefore needed. Legal instruments must also be in place to support the agriculture sector in improving manure management by incentivizing sustainable technology and capacity building.

The ugly truth is simply addressing one part of the equation doesn't solve the entire problem. Chemistry—or science as a whole—can only flourish in a multilateral environment, where societal and political dynamics do not impede the adoption of its technical breakthroughs. Like in a chemical equation, several factors can come into play between reactants and products, with a catalyst speeding up the reaction. We humans are the very catalysts that play a critical role in either preserving or exacerbating the Earth's equilibrium. Nevertheless, someone must do the dirty work to prevent further escalation of our planet's current situation. We must learn to acknowledge the rigorous efforts and experimentation that contributed to ensuring agriculture achieves long-term sustainability for future generations.

Statement on use of AI

No AI technology was used to prepare the essay.

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Finalist

Climate change a hidden virus: could green hydrogen circular economy be a solution?

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Unveiling green hydrogen as a climate change solution

Climate change is like a hidden coronavirus. Either everybody or nobody will be safe, and we don't have a choice but to work to save our planet. When we first heard about the coronavirus in 2020, we faced many challenges in our daily lives. Initially, we didn't take the small challenges seriously and didn't follow proper guidelines. Over time, we realised the importance of not ignoring the initial symptoms. This is similar to today's climate crisis. If we ignore the impact of greenhouse gases and don't make ourselves aware of this global issue, the consequences will not only affect our generation but also future generations. It's important to work towards converting our cleanest cities into the most sustainable ones.

The issue of climate change has been a prominent concern since the early nineteenth century, [1,2] and every country is committed to achieving net zero carbon emissions by 2050. As researchers, we have the potential to address this issue through innovation and by educating our society. At the current time, the whole world is facing an energy crisis and global warming. Industrial revolution and lifestyle changes accelerated global energy consumption and enhanced the level of greenhouse gases in the environment. According to a recent report, the level of CO_2 reached around 424 ppm, crossing the safe limit of 350 ppm.[3,4] This enhancement in the level of CO_2 is the primary factor in climate change, disturbing the natural carbon cycle and melting glaciers.

To consider this global issue, intending to get net zero carbon emissions by 2050, every nation is moving toward a circular economy and renewable resources. Utilising renewable resources and a circular economy will help achieve this. The most readily available natural renewable resources are wind, sunlight, water and biomass waste.[5] Each is an excellent alternative to fossil fuels and can be utilised according to the country's geographical conditions. There are several ways to reduce climate crises and help to reduce greenhouse gas emissions.

Nowadays, there is growing interest in the storage and production of hydrogen due to its high energy density, most abundant, light, and storable qualities;[6] additionally, green hydrogen emits no greenhouse gasses or pollutants directly. However, hydrogen has long been a popular topic as a fuel.[7] Hydrogen can be produced by various fuels, including nuclear, natural gas, coal and oil, and a range of industries like methanol, ammonia, steel production, and oil refining use hydrogen.[8–10] However, all are associated with CO_2 emissions and incompatible with net-zero emission goals. Therefore, we need to understand the different colours of hydrogen, which are grey, blue, and green and focus on the most promising one.[11,12] Both grey and blue hydrogen production emit CO_2, but the only difference is that grey hydrogen releases CO_2 directly into the atmosphere and contributes more to enhancing the greenhouse gas level, whereas blue hydrogen production follows the addition step of carbon capture and storage (CCS). It has various applications like power generation, energy-based industrial use, building facilities, heating, transportation and feedstock for various industrial applications. Green hydrogen means the production of hydrogen by renewable resources without the emission of any greenhouse gases, mainly CO_2, like the electrolysis of water.[13] One of the most promising mitigations is the production of hydrogen using renewable resources such as wind, solar, and biomass, known as green hydrogen. Green hydrogen, unlike grey or blue hydrogen, is a versatile source that can be used for a variety of purposes in a cleaner manner.[14] But only 4% of global hydrogen production comes from water electrolysis, while around 96% of annual global production is derived from natural gas (47%), coal (27%), and oil (22%).[15]

By incorporating green hydrogen into the global energy mix, we can reduce our dependence on high-carbon energy sources and mitigate the emissions responsible for climate change due to its numerous benefits. It could be burned to generate heat or turned into electricity using fuel cells. It functions as a low-carbon fuel or feedstock, offering a way to cut emissions where other approaches might be less practical, which helps to enhance energy security. Additionally, it serves as a clean energy carrier and can be stored with minimal loss for extended periods and easily transported over long distances, compared to grid-connected renewable electricity. It can also help to grow our economy and create new employment opportunities.

Key obstructions

We are currently encountering several challenges in adopting green hydrogen production and storage.[16–18] One is developing new technology for producing green hydrogen and scaling up renewable energy conversion. The existing technology is expensive, so we need to minimise production costs. Additionally, we need to improve the capacity of the electrolyser and develop this technology within our own country to reduce the cost of importing technology. Another challenge is the limited infrastructure and local markets for commercialised green hydrogen, which we must address. Also, we need to figure out how to transition towards a circular hydrogen economy.

Overcoming the obstructions of producing and storing green hydrogen

The focus should be on innovating the production and storage of green hydrogen and considering the global societal and policy aspects while keeping an eye on costs. The production of green hydrogen from biomass waste,[19–21] as well as from solar and wind energy,[22,23] along with storage using green alternatives like metal-organic frameworks,[24,25] ionic liquids,[26–28] and metal nanoparticles, [29–31] while considering the cost, this would be an innovative approach to global green energy transition. The main idea is to reuse as much energy as possible multiple times, and wasted energy in any form should be harnessed. This innovation is not just a purpose of talent and money but also a purpose of how urgently you are compelled to apply it, and it could be possible by adopting a green hydrogen circular economy (Figure 1).

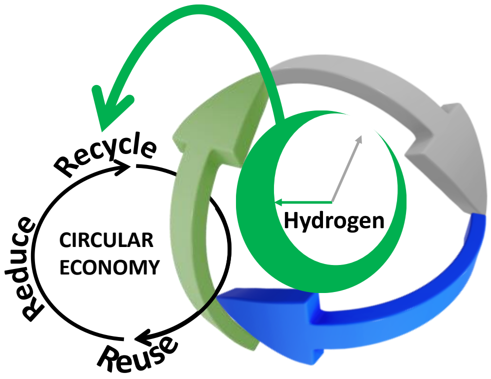

Figure 1 A simplified pictorial representation of green hydrogen circular economy.

Green hydrogen circular economy and its global societal and policy implications

The circular economy is a more environmentally friendly alternative that follows three basic principles: reduce, reuse, and recycle.[32] Currently, just 8.6% of the world economy is circular,[33] helping bridge the gap between production and ecosystem cycles. Several methods have been developed for a circular economy to produce green hydrogen.[20] For instance, biomass, agricultural food waste, waste valorisation, and by-products from various industries can serve as a renewable feedstock for dark fermentation and photo-reforming for green hydrogen production.[34–36]

We have very limited renewable energy conversion capacity, and substantial efforts are needed to minimise the usage of fossil fuels and transition to renewable energy. Countries like South Asia, western regions of South America, and Middle East Africa are the most promising sites for green hydrogen production due to the abundance of solar and wind energy there.[37,38] However, over 90% of the global hydrogen is currently produced using fossil fuels,[39] indicating that less than 10% comes from renewable energy sources. Clean hydrogen technology is available, but the cost remains a challenge for implementing it on a larger scale. Therefore, particular aspects could be required to build a future roadmap for achieving net zero carbon emissions by 2050.[40–42] The first aspect is to educate society and lead by example. We need to not only transition the city's economy and technology but also shift their mindset by prioritising common goals; we need to raise global awareness. Also, collaborative efforts should be required to address the issue of green hydrogen production. Endorsement of investment policies should be focused on the early-stage proof of concept approach, private sectors, forging partnerships, local markets, and upgrading manufacturing. By adopting the above aspects, we are not only reshaping the way to utilise renewable resources for global energy transition but also redefining our connection with the environment.

Statement on use of AI

No AI technology was used to prepare the essay.

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Finalist

The Earth's rapid demise- there is no planet B

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"Save the World", "Don't be a fossil fool", "The Earth can't wait!", "Better environment, better tomorrow…" these are only a few examples of slogans that have been widely popularized in efforts of drawing awareness towards the importance of saving the Earth and all its resources. From environmental campaigns, to climate change protests, one would think the global society would be intentional about decarbonization initiatives, to ensure the Earth is habitable for future generations. Are we really doing enough though, or is it all a façade on a global issue, that if not addressed will exacerbate the Earth's rapid demise?

Researchers like Nunes,[1] have attributed the Earth's rapid deterioration to increased levels of greenhouse gases like carbon dioxide, largely caused by the combustion of fossil fuels for energy generation, as well as deforestation and agricultural practices, amongst other things. These emissions have resulted in global warming and climate change, increasing surface temperatures and water shortage, and reducing the prospects of a habitable planet. Unfortunately, there is no planet B to relocate to, nor is there a quick fix solution. Scientific intervention is therefore required to remedy the damage that has been done and to provide solutions for dealing with carbon emissions going forward.

Fortunately, all is not lost, chemical scientists have taken it in their stride to decarbonize energy generation. Osman et al.,[2] explained that by developing advanced hydrogen production technologies, scientists can replace fossil fuels in various industrial processes, including ammonia production, refining and steelmaking without any significant emissions. Xia et al.,[3] reported that the development of electrochemical technologies has also offered promising pathways for decarbonizing industrial processes by using renewable electricity to drive chemical reactions and produce desired products without any carbon emissions. Impressively, chemical scientists have also contributed to developing advanced materials with enhanced properties, durability, and performance, which enable the adoption of low-carbon technologies in industrial applications.

With technological advancements, industries have also started playing their part by implementing industry-specific measures and climate-smart practices to reduce their carbon footprint. For instance, agricultural operations are being decarbonized by utilizing renewable energy sources such as solar, wind, and biomass for irrigation, machinery, and heating, thereby reducing reliance on fossil fuels. Additionally, dietary manipulation and proper manure management can curb the emission of methane. Galgani et al.,[4] also reported that due to the development of techniques such as anaerobic digestion, composting, and biochar production, chemical scientists can capture methane for energy conversion while reducing odour and greenhouse gas emissions. While, Cordeiro et al.,[5] reported that controlled-release of fertilizers, cover cropping, and crop rotation can improve nutrient efficiency and thus reduce the need for synthetic fertilizers, Torres et al.,[6] described simple practices like integrating trees and perennial vegetation that can also be used to sequester carbon in biomass and soil.

According to Dziejarski et al.,[7] sustainability can be enforced in large-scale manufacturing practices as well by deploying carbon capture and storage technologies to deal with emissions using materials including metal oxides, metal organic frameworks and zeolites. As luck would have it, the captured carbon dioxide can be utilized in various applications as reported by Ghiat and Al-Ansari,[8] such as enhanced oil recovery, carbonation of concrete, and production of synthetic fuels and chemicals. Large-scale manufacturers can also make use of green chemistry principles to reduce the emission of carbon into the atmosphere. As explained by Anastas and Beach,[9] green chemistry leads to lower carbon emissions across the entire lifecycle of chemical products and processes as it promotes the use of renewable feedstock, energy-efficient processes, and reduced waste generation. Industrial green chemistry can therefore be used to adopt circular economy principles, such as product design for durability, reuse, and recycling, minimizing resource consumption and waste generation in manufacturing.

Although it helps, clearly salvaging the Earth's resources and reducing greenhouse gas emissions is going to take more than just planting a few trees, using long lasting bulbs and taking shorter showers. Decarbonization in industries requires urgent and concerted action at global, national, and local levels to reduce emissions, protect vulnerable communities and ecosystems, and build resilience to the impacts of climate change. Chemical scientists can play their part in the decarbonization mission by optimizing and prioritizing research on alternative energy solutions as well as carbon capture, storage and utilization. They can also lead the generation and spread of novelties to peers and the public through manuscripts, conferences and community engagements. Additionally, mitigation strategies can reduce greenhouse gas emissions by transitioning to renewable energy sources, improving energy efficiency, and implementing policies to limit carbon emissions, while adaptation strategies can strengthen resilience to the impacts of climate change.

By leveraging chemistry findings and innovations, it is possible to develop and implement effective strategies for decarbonizing industrialization processes like large-scale manufacturing and agricultural practices. This would contribute to the global efforts of mitigating climate change and transitioning towards a sustainable and low-carbon economy. Although it has deteriorated significantly, the Earth still has so much to offer and can be habitable for generations to come. Perhaps it is time to change – after all, there is no planet B.

Statement on use of AI

Al technologies were used in the preparation of the paper for inspiration, structure and in ensuring adherence to critical aspects of the topic at hand.

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Finalist

Transformation of main greenhouse gases into value-added products to preserve life on Earth

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Methane (CH_4) and carbon dioxide (CO_2) are sources of carbon (and hydrogen, in the case of CH_4) widely available and underutilized. Carbon dioxide is a combustion product indiscriminately released into the atmosphere. More than 90% of globally extracted methane is eventually burned, contributing also to CO_2 emissions.[1] The burning of fossil fuels for energy obtention, the manufacturing of commodities such as steel, aluminium, and glass, or the cement and chemical production, among others, produce large amounts of carbon dioxide. On the other hand, methane is the main greenhouse gas emitted in the agrarian sector mainly by enteric fermentation of ruminant animals as well as by manure management. Anyway, CO_2 and CH_4 are the main components of the biogas obtained from the anaerobic digestion of organic matter whether from urban, industrial, or agricultural waste.

CH_4 and CO_2 are also the main primary greenhouse gases directly responsible for the global warming.[2,3] The Intergovernmental Panel on Climate Change (IPCC) estimates that CH_4 has a Global Warming Potential (GWP) around 21-28 times higher than CO_2 over a 100-year period. This means that CH_4 is significantly more effective at trapping heat in the atmosphere compared to CO_2. However, CH_4 has a shorter atmospheric lifetime (12 years) than CO_2 (hundreds to thousands of years). Therefore, although CH_4 has a greater GWP per molecule, its overall impact on global warming over longer time scales might be somewhat mitigated by its shorter atmospheric lifetime compared to CO_2. In any case, CH_4 and CO_2 emissions into the atmosphere have been for decades and continue being above the 90% of the total anthropogenic releases. This trend persists because greenhouse gas emissions are inherent to the unstoppable human progress and development which unavoidably relies on fossil fuel combustion. In fact, regarding the energy global consumption, the fossil fuel employed to produce energy (as the sum of coal, natural gas, and oil) reached more than 84%, in 2018, of all primary energy sources.[4] So, replacing or reducing this increasing percentage does not seem very simple to be done from one day to the next. Meanwhile, the average temperature of the planet surface continues to rise, shortening the path to the 2°C increment: the threshold beyond which our planet will suffer irreversible and ravaging impacts such as biodiversity extinction, rising sea levels, staple food shortage, and potable water scarcity, among many others.[5,6]

In response, there is a pressing need to incentivize industries to repurpose methane and CO_2 as raw materials for high-demand products obtention, offering a glimmer of hope in mitigating their harmful emissions. In this context, CH_4 dry reforming reaction is able to convert CH_4 and CO_2 into syngas (H_2 and CO) which could serve as a precursor for liquid fuels and chemicals production through downstream steps like Fischer-Tropsch or methanol synthesis.[7,8] In fact, syngas is the primary industrial application of CH_4.[9] Nevertheless, its energy-intensive consumption (and its derived high expenses) hampers methane utilization as feedstock beyond 10%.[1] Thus, the scarce industrial processes directly transforming CH_4 are currently limited to acetylene,[10] chlorinated methane[11,12] and hydrocyanic acid[13] production. Industrial processes directly transforming both CH_4 and CO_2 into chemicals do not currently exist. In this sense, research endeavors must be intensified to explore direct CH_4 routes (preferably including CO_2 simultaneous transformation) avoiding extreme conditions inherent to favor total combustion products. In spite of the critical importance of this matter, experimental research works directly transforming CO_2 and CH_4 into oxygenated hydrocarbons are scarce.[14–20] Among the limited studies, some collect homogeneous catalytic reactions driven by non-thermal plasma[14–17] which is an ionized gas (conducting electricity) composed of positively charged ions and free electrons. However, such plasma reactions involve free radicals into the plasma phase which inherently restrict the selectivity control, giving rise to further oxidation to total combustion products (including CO_2). Regarding purely heterogeneous catalysis, acetic acid formation has been obtained as the main reaction product from CO_2 and CH_4 direct transformation.[18–24] Rabie et al. [22] reported the formation of 23.7 $g \cdot kg_{CAT}^{-1} \cdot h^{-1}$ of acetic acid at 500°C by employing a Cu^0-K-ZSM-5 zeolite as catalyst; and Ding et al.[20] obtained 2.4 $g \cdot kg_{CAT}^{-1} \cdot h^{-1}$ of acetic acid at 200°C by using Pd/SiO_2 as catalyst. No literature has been found concerning direct CH_4 and CO_2 coupling into other oxygenated hydrocarbons apart from acetic acid by pure heterogeneous catalytic processes.

Within the context above, the research that I work in has achieved the best results reported so far regarding the direct transformation of CH_4 and CO_2, at low temperature and even below ambient pressure.[25,26] Specifically, the work of Montejano-Nares et al.,[25] published in 2024, details the direct and simultaneous transformation of CH_4 and CO_2 into high-value-added products (acetone, dimethyl ether, and acetic acid) at temperatures ≤ 150°C (below ambient pressure), with the highest yields reported to date, by employing a $PdAg_4$-$Fe_{3-\delta}O_4$ nanocomposite as catalyst (Reaction 11 in Table 1). Combining the experimental catalytic results with theoretical thermodynamic studies, dimethyl ether was determined as a secondary reaction product, obtained from CO_2 and acetone (this latter appearing as a primary product). These and many other reaction results of this research have led to the granted patent ES 2933754:[26] the first in the world to claim a process for the direct conversion of CO_2 and CH_4 into oxygenated hydrocarbons with more than one carbon atom, such as ethanol, acetone, acetic acid, propanol, dimethyl ether or butanol (Figure 1 and Table 1).

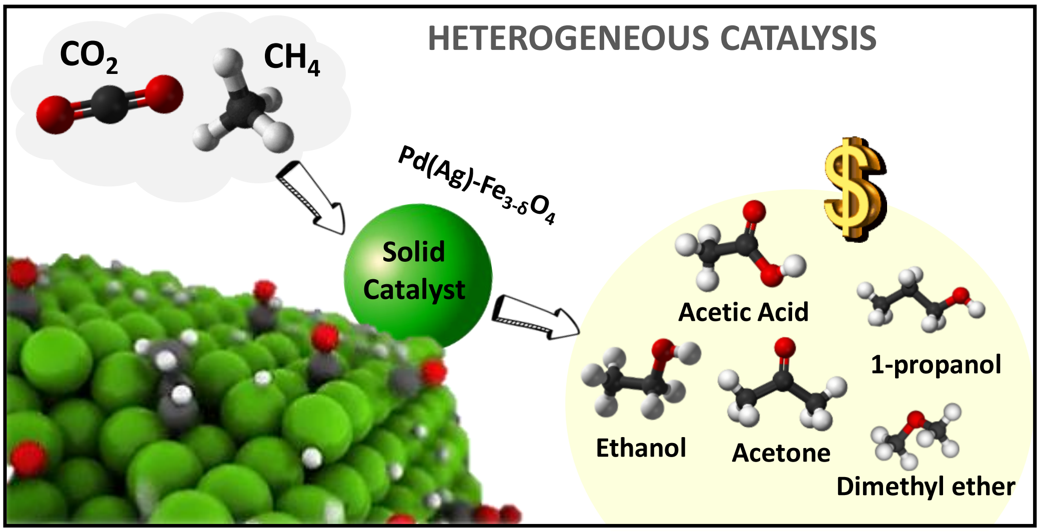

Figure 1. Representation of the direct transformation of CH_4 and CO_2 by heterogeneous catalysis into different oxygenated hydrocarbons, employing a nanocomposite based on Pd(Ag)-$Fe_{3-\delta}O_4$ as catalyst

Table 1. Reactivity results of CH_4 and CO_2 direct transformation into oxygenated hydrocarbons[26]

Reaction	Catalyst	Tª (°C)	Productivity ($g_{PROD}\cdot kg_{CAT}^{-1}\cdot h^{-1}$)				
			Ethanol	Acetone	Acetic acid	1-propanol	DME
1	3%Pd-$Fe_{3-\delta}O_4$	250	2.4	23.4	19.3	0.8	-
2	3%Pd-$Fe_{3-\delta}O_4$	200	6.1	2.6	0.3	0.4	-
2	3%Pd-$Fe_{3-\delta}O_4$	250	8.1	3.4	-	2.6	-
3a)	3%Pd-$Fe_{3-\delta}O_4$	250	11	44.3	4.6	6	-
4	3%Pd-$Fe_{3-\delta}O_4$	200	8.7	1.1	0.2	1.6	-
4	3%Pd-$Fe_{3-\delta}O_4$	250	18.8	1.5	0.1	12.9	-
5	2%Pd-$Fe_{3-\delta}O_4$	200	3.2	0.3	-	0.4	-
5	2%Pd-$Fe_{3-\delta}O_4$	250	13.1	0.2	-	2.6	-
6	1%Pd-$Fe_{3-\delta}O_4$	200	13.9	0.1	-	2	-
7	3%$AgPd_4$-$Fe_{3-\delta}O_4$	200	1.3	2.7	-	-	-
8	3%$AgPd_4$-$Fe_{3-\delta}O_4$	200	6.6	0.8	-	2.9	-
8	6%Pd-$Fe_{3-\delta}O_4$	250	12.9	5.6	<0.1	6.7	-
9	3%Pd-$Fe_{3-\delta}O_4$	200	0.3	0.5	-	<0.1	-
10b)	3%Pd-$Fe_{3-\delta}O_4$	250	1.3	2.9	0.6	0.2	-
11	3%Pd-$Fe_{3-\delta}O_4$	120	-	5.7	0.1	-	3.4
12	3%Pd-$Fe_{3-\delta}O_4$	250	13.4	0.7	-	4.7	-

a) ethylene traces (selectivity 1.6%). b)1-butanol traces (selectivity 0.8%). Acronyms: DME (dimethyl ether). Reaction pressure: 1.2 bar (0.02 bar for Reaction 11)

The oxygenated hydrocarbons obtained are high value-added products whose annual production reaches millions of tons: around 110, 21.5, and 7.4 million tons per year of ethanol,[27] acetic acid,[28] and acetone,[29] respectively. For instance, ethanol is one of the most versatile oxygen-containing organic compounds due to its diverse range of applications, serving as a multi-purpose clean fuel, as well as solvent, antiseptic, beverage, antifreeze, and as a precursor for various other organic chemicals.[30] Acetone is the simplest and most commonly used ketone, employed as gasoline additive, cleaning agent, and as an important solvent in various industries (pharmaceuticals, cosmetics, and chemical manufacturing), among others.[31] Acetic acid is an organic compound and a weak acid, commonly found in vinegar, widely used in the food industry (as a preservative and flavoring agent), as solvent in the production of various chemicals, as a cleaning agent, as well as in the production of plastics, textiles, and pharmaceuticals, among other uses.[32] Thus, the obtention of value-added products (such as ethanol, acetone, or acetic acid) from CH_4 and CO_2 has a real potential to rekindle economic interest in harnessing these greenhouse gases, offering a thread of hope for mitigating their indiscriminate emissions, which are primarily responsible for the relentless global warming and its catastrophic consequences.

Statement on use of AI

No AI technology was used to prepare the essay.

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Finalist

Chemical sciences for future zero-carbon energy and zero-greenhouse gas in large-scale manufacturing and agriculture

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The importance of chemical sciences in decarbonizing energy conversion and mitigating greenhouse gas emissions from large-scale manufacturing and agricultural processes has been emphasized by the urgency of addressing climate change.[1,2] This essay explores the diverse contributions of the chemical sciences in these areas, highlighting key advances, challenges, and potential pathways to a sustainable future.

The chemical sciences have been instrumental in advancing clean energy technologies, particularly in the field of renewable energy. For example, innovations in materials science have led to remarkable advances in solar photovoltaics. The development of next-generation solar cells, such as perovskite solar cells, promises higher efficiencies and lower costs,[3] making solar energy more accessible and competitive. In addition, energy storage solutions are essential for effectively integrating intermittent renewable energy sources such as solar and wind into the grid. The chemical sciences are contributing significantly to the development of advanced battery technologies, including lithium-ion, solid-state, and flow batteries.[4–6] These innovations increase energy storage capacity, improve cycle life, and support grid stability, facilitating the widespread adoption of renewable energy systems.

Advancements in fuel cells, such as proton exchange membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs), hold promise for decarbonizing sectors like transportation and stationary power generation, in addition to solar and battery technologies. These fuel cell technologies can efficiently convert hydrogen or other fuels into electricity with zero-carbon emissions. Research and development efforts in the chemical sciences aim to improve fuel cell performance, durability, and cost-effectiveness, making them a viable solution for clean energy.[7]

Although transitioning to renewables is crucial, it is equally important to address emissions from existing fossil fuel-based infrastructure. Carbon capture and storage (CCS) technologies provide a pathway to reduce carbon dioxide (CO_2) emissions from industrial processes and power plants. The development of effective CCS systems, including capture technologies, transportation methods, and storage solutions, relies heavily on chemical sciences.[8] Post-combustion capture is one of the most widely studied CCS techniques. It involves capturing CO_2 from flue gases using solvents. Chemical engineers and scientists are continuously optimizing capture materials and processes to improve efficiency, reduce energy requirements, and lower costs.[9] In addition, pre-combustion capture methods, such as gasification coupled with CO_2 capture, can reduce emissions in integrated gasification combined cycle (IGCC) power plants and industrial facilities.[10] Moreover, advances in carbon capture and utilization (CCU), which is the most effective carbon-neutral technology for the heavy industry sector, provide opportunities to transform captured CO_2 into valuable products, such as fuels and petrochemicals.[11] Chemical sciences are driving research in CO_2 conversion catalysts, electrochemical processes, and mineralization technologies. These pathways for CO_2 utilization contribute to the circular economy and help mitigate greenhouse gas emissions.[12]

As a challenging issue, large-scale manufacturing processes are significant contributors to greenhouse gas emissions and environmental impact. For overcoming this problem, green chemistry principles guide the development of sustainable manufacturing practices that prioritize resource efficiency, waste minimization, and reduced environmental footprint. Chemical sciences play a significant role in advancing green chemistry technologies across diverse industries.[13] One area of focus is the development of bio-based materials and chemicals as alternatives to fossil fuel-derived products. Biorefineries, utilizing biomass feedstocks such as agricultural residues, forest biomass, and algae, produce biofuels, bioplastics, and biochemicals through enzymatic or microbial processes. Chemical engineers optimize biorefinery operations, enhance product yields, and improve the overall sustainability of bio-based supply chains.[14] Additionally, process intensification techniques, such as spinning disc reactors and micro-reactor systems, enable more efficient and environmentally friendly chemical production. These innovations reduce energy consumption, waste generation, and environmental impact compared to traditional processes.[15]

Agriculture is a significant source of greenhouse gas emissions, primarily methane (CH_4) from livestock digestion and nitrous oxide (N_2O) from fertilizer use. Chemical sciences play a crucial role in promoting agricultural sustainability by developing innovative solutions to reduce emissions and improve resource efficiency. Precision agriculture technologies utilize sensors and data analytics to optimize crop management practices and minimize inputs such as water, pesticides, and agrochemicals. In addition to soil management, the use of nitrogen fertilizer can be decreased by accurately targeting nutrient application. This means can reduce N_2O emissions associated with fertilizer application.[16] Furthermore, the use of fertilizer formulations, such as slow-release and controlled-release fertilizers, can improve nutrient absorption efficiency and reduce nutrient losses to the environment.[17] Chemical sciences have also contributed to the development of feed additives and management practices that mitigate methane emissions from ruminant animals in livestock farming.[18] Methane inhibitors, such as feed supplements containing compounds like 3-nitrooxypropanol, can mitigate methane emission without compromising animal health or productivity.[19] Strategies for soil carbon sequestration (SCS) can contribute to carbon storage in agricultural soils, where SCS is the process of capturing carbon-containing substances from the atmosphere and storing them in soil carbon pools. Additionally, the optimizations of nutrient and soil management is essential for SCS, while also promoting co-benefits for agronomy and the environment. This requires the contribution of the structure of the soil microbial community.[20] Chemical analyses and modeling techniques can be used to assess the potential for SCS and guide sustainable land management practices for climate change mitigation.[21]

In summary, the chemical sciences are essential to the transition to a low-carbon economy and to mitigating the impacts of climate change. The chemical sciences provide the significant contribution to decarbonizing energy conversion and reducing greenhouse gas emissions from large-scale manufacturing and agricultural activities through advancements in clean energy technologies, carbon capture and storage, sustainable manufacturing processes, and agricultural innovations. Continued research, innovation, and collaboration across scientific disciplines and industries are crucial to accelerating progress towards a sustainable and climate-resilient future.

Statement on use of AI

The author declares that ChatGPT was used to improve grammars, language, and readability of the essay.

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Finalist

A planetary battle against climate crisis: myth or a chemical journey towards sustainability?

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Introduction

A world divided by factions, fighting for control over limited resources on a desert planet, with clean water only a luxury. This fictional world[1] of Frank Herbert's 'Dune' could portray a thought-provoking prelude to Earth, highlighting current challenges of climate change, energy crises and resource scarcity (Figure 1). For Earth's population, technology has undeniably improved the human quality of life. Medicine, agricultural fertilizers and synthetic materials are just few of the many advancements brought by chemical science. While driving global progress, it also draws attention to the negative impacts of greenhouse gasses on global warming and the environmental consequences of pollutants. Global warming causes shifts in earth's natural balance, as is becoming increasingly evident by rising sea levels, abnormal weather phenomena and prolonged periods of drought.[2] While a scenario like that in Dune, still seems distant science fiction, it offers a glimpse into a future where the planet's assets are beyond control and irreversibly depleted.

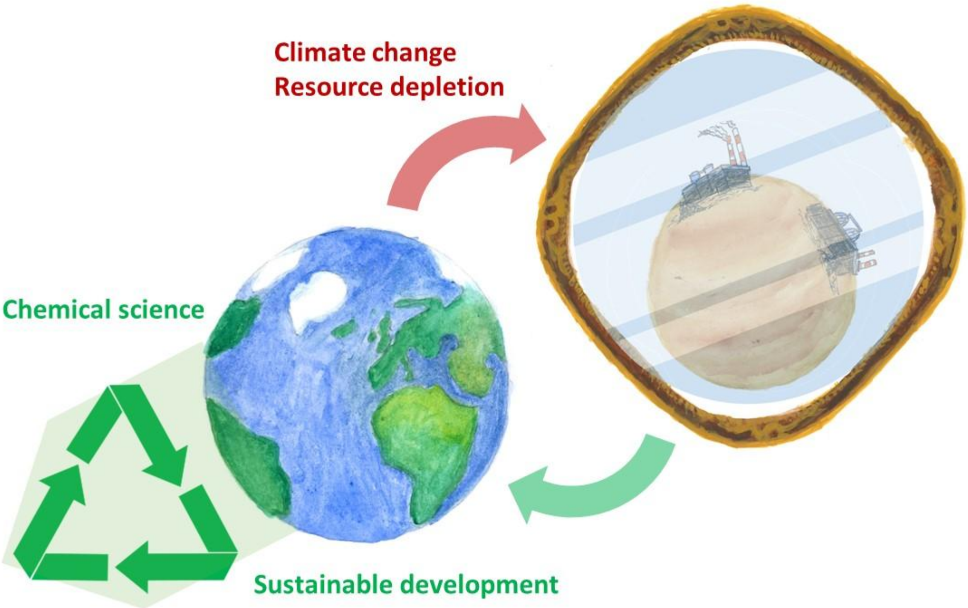

Figure 1 Thematic portrayal and mirroring of Earth to the fictional world of Dune

Manmade greenhouse-gas emissions, dominated mostly by CO_2, but also methane (CH_4), originate from our reliance on fossil fuels for energy generation, transportation and large scale manufacturing.[3] For electricity generation, the combustion of oil, gas or coal can at most reach 45% efficiency.[4] Growing energy demands, by industrialization and an increasing population, led to a total CO_2 emission of 37.4 gigatons by 2023, mostly produced over the last century.[5] To protect Earth's resources and natural ecosystems, it is crucial for the global population to actively seek solutions. Atmospheric carbon levels should be controlled to mitigate the effects of climate change. At the policy level, already ambitious climate laws to cut Europe's emissions by 55% in 2030 are enacted, aiming for climate neutrality by 2050.[6] However, to achieve these goals with the current scale of emissions, collaborative effort between scientists, industries and global policymakers is required. Chemical science plays a fundamental role in delivering technologies that facilitate a green transition. This essay will focus on the thriving potential of chemistry to contribute to decarbonize large-scale manufacturing for a sustainable future.

Circular carbon strategies for sustainable fuels

Industrial high-temperature processes like steam cracking, for light olefin production from hydrocarbons, and the Haber-Bosch process, for ammonia (NH_3) production from nitrogen and hydrogen, have high energy requirements.[7] Typically, the chemical industry heavily relies on a limited set of fossil fuel derived chemicals as starting materials for production. These include light olefins such as ethylene, propylene and butadiene and aromatics like benzene and toluene.[8] Also agricultural fertilizers use ammonia as base chemical. Hydrogen, which is often proposed as a clean fuel for energy storage, is mostly supplied by syngas. This syngas mixture of CO and H_2 is prepared by the catalytic reforming of fossil methane and has a large carbon footprint. All of this clearly shows that decarbonizing the chemical industry is practically impossible, since organic chemical production requires a carbon source. Instead, the industry could change to renewable fuels to defossilize carbon use, and develop carbon circularity for supplied chemicals (Figure 2). At the moment, there is a strong take-make-dispose approach of valuable resources. Feedstock is either lost as CO_2 emissions during manufacturing or as chemicals, that are typically incinerated at end-of-life.[9] Therefore, efficient carbon capture directly at installations could limit emissions. Despite 400 million tons of CO_2 captured annually, this is only 0.12% of the total emissions.[10] Therefore, focus on new technology for capture may further develop techniques for adsorption of CO_2 on solid supports (*e.g.* on zeolites and metal organic frameworks), or in separating this compound from combustion gasses using membranes or solvent absorbents.[11] Mineralisation can effectively prevent release to the environment. Developments have been made to capture CO_2 as $CaCO_3$, a base material for the cement industry.[12] Also investigations utilize amine compounds, such as N-methyldiethanolamine, for CO_2 sequestration in cement containing building materials.[13] Amines are known for their ability to chemically absorb CO_2. The concept of 'synthetic trees' has been proposed for constructs containing such technology for capture and storage.[14,15] Achieving true carbon circularity is only feasible by CO_2 conversion into valuable base chemicals and fuels. By catalysis and electrochemistry several methods for conversion of CO_2 into chemicals that are high in demand, like methanol, carboxylic acids and urea, show promise.[16] While operational costs are currently higher, scaling electrochemical processes can be more energy efficient than traditional thermal heating. A notable example is the construction of electrically heated steam cracking furnaces on the BASF site in Ludwigshafen (Germany), powered by wind as renewable energy source.[17–19] Green hydrogen can be derived from water electrolysis and methanol production from CO_2-capture may provide an alternative energy storage platform, since this liquid form of C1-chemical can be transported and used when needed. Processes for methanol-to-hydrocarbon conversion also open up sustainable pathways for production of fuels such as olefins, gasoline and aromatics.[20]

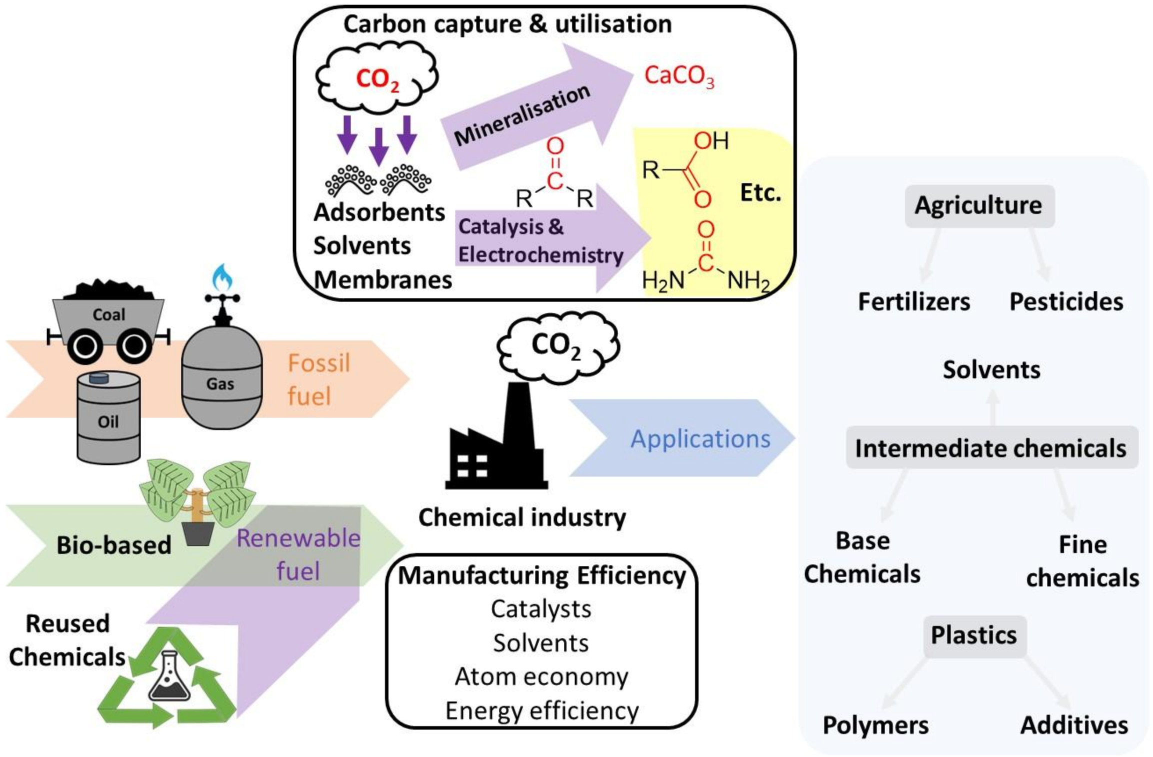

Figure 2 Concept of reducing the carbon footprint of the chemical industry by efficient manufacturing, renewable fuel and carbon capture technologies

Sustainable development initiatives must also address the complex issue of waste management. The widespread use of commercial plastics that are non-biodegradable is an urgent environmental concern. With plastic production already surpassing 400 million tons last year, it is an ever-increasing loss of valuable resources. Packaging, constituting 40% of plastic production, is frequently designed for single-use purposes (Figure 3). At end-of-life, plastic packaging materials are often difficult to recycle because they contain additives, such as inks, adhesives and often comprise of multilayer plastics. Hence, these physical mixtures of different plastics that are bound to one another are often incinerated as a means of energy recovery as no other option exists than landfill.[21] Either way, these current options are deplorable, and recycling routes should be further developed for full reuse of materials instead of disposal. Of the collected plastics for recycling, generally, mechanical recycling of polymers leads to lower value products and can only be applied to few waste streams with pure material.[22] Recycling plants that typically use near-infrared detection for recognition of the types of plastic, cannot distinguish multilayers or black coloured materials. To solve these limitations for recycling plants, novel methods for dissolution of plastics in solvents are in active development. So called 'solvent-targeted precipitation and recovery' allows isolation of plastics from mixed waste streams. This technique has recently been reported for typical food wraps of polyethylene terephthalate (PET)-polyethylene (PE) for recovery of the main plastics, but also for selective splitting of adhesive glues, that join the different layers in the packaging material.[21,23] These approaches may also show utility for textile recycling, that accounts for an annual 92 million ton of waste.[24] Since textiles often are blends of synthetic polymers (*i.e.* polyester, nylon and PUR) with natural polymers like cotton or wool, recovery and reuse of these components using solvents can potentially avoid large amounts carbon loss.[25] Streamlining these separation steps are a critical in combating challenges posed by the complexity of plastic waste. However, this step alone is insufficient, as also emphasis should be placed on chemical recycling techniques.

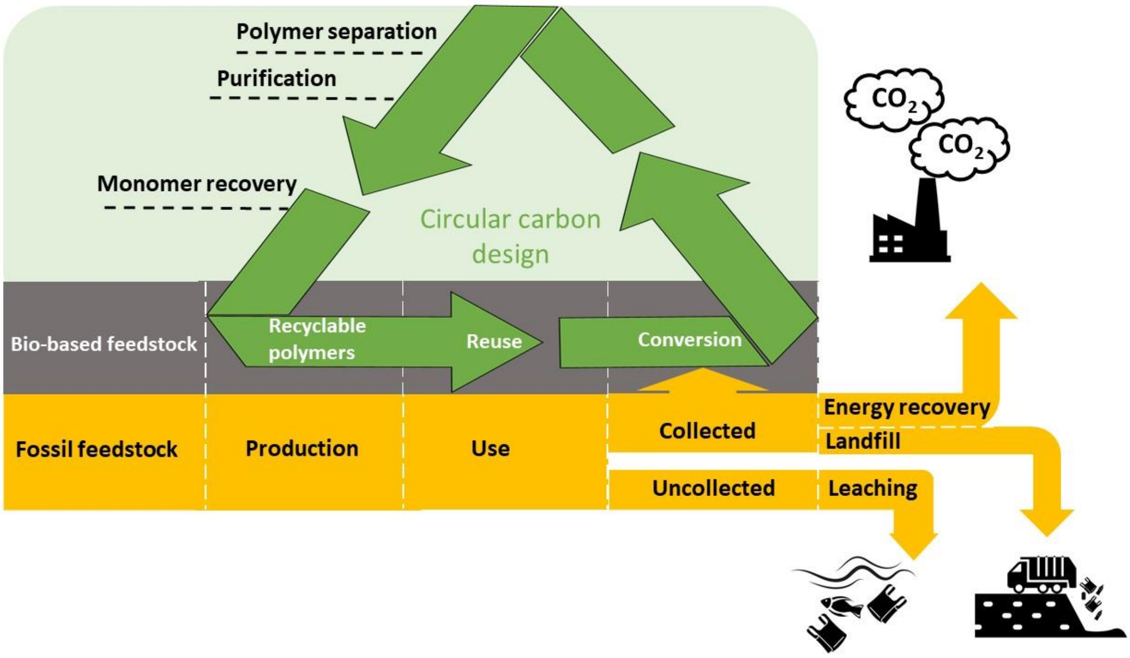

Figure 3 Circular carbon design for plastic waste management

By effectively breaking down plastic polymers into their constituent monomers or converting them into reusable industrial chemicals, we can minimize the environmental impact of plastic waste and enable a circular carbon use. Addition polymers that contain heteroatoms within the polymer chains, such PET and polyurethanes (PUR), are viable candidates for chemical recycling by splitting using solvents in industry, (*e.g.* by alcoholysis or hydrolysis).[26] However, currently the majority of commercial plastics are polyolefin based, including primarily PE, polypropylene (PP) and polyvinyl chloride (PVC) for which no efficient depolymerisation techniques exist that allow monomer recovery. Some developments for PE recycling include catalytic dehydrogenation to form functional double bonds in the polymer, allowing chemical recycling by C-C bond splitting in subsequent steps (*e.g.* by metathesis).[27] However, the C-H bonds in PE require tough recycling conditions. A solution could be the functionalisation of PE with heteroatoms, to allow more efficient splitting. A recent investigation developed a PE synthesis that includes reactive carbonyl (keto-)groups on the polymer backbone. Subsequent postpolymerization functionalisation by Baeyer-Villiger reaction can effectively to convert this keto-PE into a polyester, that undergoes hydrolysis during environmental degradation.[28] While chemical PVC recycling is often impeded by aromatic char formation due to its high chloride content, developments are focussed on a selective conversion of this polymer to PE-like materials, that have a high value for reuse by industy.[29,30] Hence, commercial polymers should be specifically designed for recyclability by catalytic conversion at end-of-life to close the carbon cycle.

Conclusion

As the effects of climate change loom ever larger over our planet, the call of action grows ever more immediate. By innovating in materials, processes, and renewable energy, we can reduce emissions and create a more sustainable future. Harnessing the power of chemistry can navigate towards a future that is in harmony with the planet, rather than its expense. While scenarios as in 'Dune' serve as cautionary tales, amidst these challenges lie opportunities for transformative change, driven by the adaptability of human innovation.

Statement on use of AI

No AI technology was used to prepare the essay.

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Finalist

Chemical Sciences: a Par Excellence Practice for Decarbonization

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Introduction

The evolution-altering mastery of fire, enabling warmth, food preparation, predator deterrence, and expansion into diverse environments, began approximately 2 million years ago with *Homo sapiens*.[1] However, the onset of the Industrial Revolution in the 18th century in Britain marked humanity's inaugural leap toward global modernization.[2] This has resulted in the contemporary world where automation dominates industries instead of human intervention, fostering exponential growth and enhancing the global economy. Nurkse[3] believed advancements in agriculture were crucial for industrial growth, nurturing the quality of life of modern human beings through both revolutions. This has led to a global population explosion, with the current population estimated to be around 8 billion, growing at a staggering rate.[4]

The demands of such a large population are also driving increased supply by industries and agriculture, leading to the accumulation of agro-industrial waste. Though agro-industrial waste can be recycled into value-added products like biofuels, pigments, and compost, achieving 100% recycling is not feasible. As a result, agricultural activities contribute about 30% of total greenhouse gas emissions.[5] The primary components, nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4), all play roles in climate change and global warming, significantly affecting the sustainability of agricultural production systems. The environmental damage has deeply concerned stakeholders such as policymakers, environmental health specialists, and the public. The pressing necessity to address climate change has brought the chemical sciences into focus. By prioritizing sustainable development and promoting recyclability through chemical processes, we can safeguard planet Earth and its declining resources. However, achieving "net-zero carbon" requires a collective effort from nations and individuals to improve daily activities to preserve nature. The essay explores how chemical sciences can lead the charge in decarbonizing energy conversion and curbing emissions from large-scale manufacturing and agriculture on a global scale.

Chemical sciences: stairway to decarbonization

The primary greenhouse gases, CO_2 and CH_4, constitute approximately 91% of the total, with CO_2 being the predominant component.[6] Global energy-related CO_2 emissions increased by 1.1% in 2023 compared to 2022, reaching a new record high of 37.4 billion tonnes.[7] The atmospheric concentration of CO_2 reached a staggering 425 parts per million (ppm) as of February 2024.[8] Fortunately, of all the CO_2 emitted into the atmosphere, only about half remains, contributing to climate change, while the other half is absorbed by CO_2 sinks on land (through vegetation uptake via photosynthesis) and oceans (through diffusion).[9] The remaining half that persists in the atmosphere contributes to global warming, resulting in biodiversity loss, drought, food scarcity, extreme heat, rising sea levels, and numerous other threats.

Here, the concept of “net zero carbon” plays an important role. According to this concept, the CO_2 emissions generated by human activities released into the atmosphere should be offset by using that same amount of CO_2 to produce value-added products through chemical processes. The amount of CO_2 generated can be minimized by utilizing alternative clean energy technologies like solar PV, wind, nuclear power, heat pumps, and electric cars to some extent. The challenge of harnessing atmospheric CO_2 to minimize the total concentration could be addressed through advancements in chemical sciences. The main components of reaching decarbonization (Figure 1) include electrification, hydrogen and hydrogen-based fuels, renewables, carbon capture, utilization and storage, energy efficiency, and behavioural changes.[10]

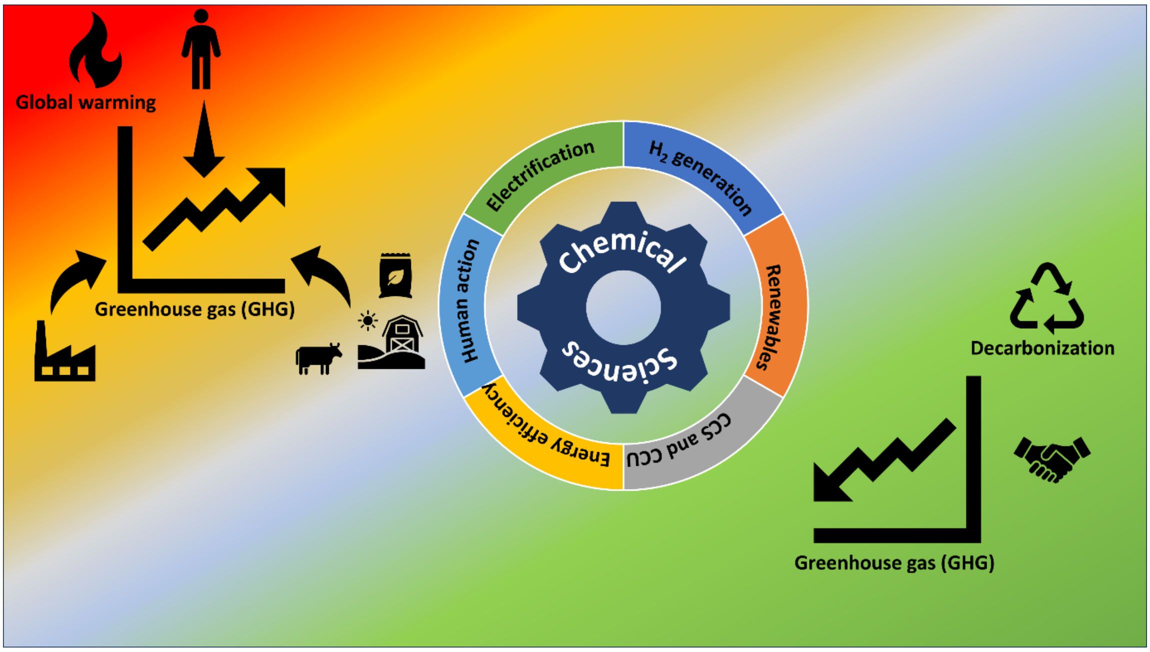

Figure 1 Components of achieving decarbonization to reduce global warming.

The industrial electrification process entails replacing fossil fuels with electricity-driven processes. For example, a gas boiler can be substituted with an electric boiler, which is not only cost and energy-efficient but also durable. It is believed that nearly 50 percent of the fuel used by industrial companies for energy could be replaced with electricity using existing technologies.[11] Recent advancements in industrial electrification have led to the development of photoelectrocatalytic (PEC) approaches for decarbonization. The key benefits of this technique briefly include the following: (a) integration of the PEC design into solar flow battery, where solar energy is stored as chemical energy, (b) doubling the efficiency by producing the same product on both electrocatalytic sides, (c) electro-driven production of green H_2 from biomass generated from agricultural waste, (d) fertilizers (N_2 based) directly from the air, (e) electrocatalytic direct synthesis of ammonia as H_2 vector, which reduces the transport and storage cost of H_2.[12] These practices can effectively minimize the generation of carbon-based waste in the industry.

Hydrogen, on the other hand, is considered an excellent fuel due to its very high energy content of 120 MJ/kg, which is nearly three times that of gasoline (44 MJ/kg).[13] H_2 is expected to mitigate future shortages of traditional energy resources (TER) and is also considered the cleanest energy source, as burning hydrogen produces water. While the Sun's atmosphere is blessed with H_2 fuel, Earth's atmosphere has a very low abundance of around 0.6 ppm.[14] Therefore, the only way to obtain H_2 is by converting available resources through catalytic reactions. Methods for generating hydrogen include (a) water splitting via electrolysis, thermolysis, and photolysis, (b) thermochemical conversion by pyrolysis of biomass, gasification of biomass, and (c) biological conversion by biophotolysis and fermentation.[15] The production of hydrogen is associated with another challenge: storage and transport. This is due to the low density of hydrogen, requiring very high pressures to store it in both gaseous and liquid forms. In earlier stages, researchers have utilized metal hydrides (such as MgH_2) as hydrogen storage materials, which have the drawback of requiring high decomposition temperatures. Recent advances have led to the development of physiosorbed hydrogen storage materials like carbon nanotubes, graphene, and metal-organic frameworks (MOFs), requiring less thermal energy to deliver hydrogen. The latest focus is on developing liquid organic hydrogen carriers (LOHCs) and inorganic carriers like NH_3 for their high storage capacity and ease of long-distance transport.[16]

We rely on traditional energy resources (TER) such as coal, natural gas, and oil, which are finite, contributing to greenhouse gas emissions. Instead of TER, we can utilize renewable energy resources (RER), which are not only unlimited but also cause little to no harm to the environment. Renewable energy sources include wind, hydropower, solar, biomass, and geothermal energy.[17] Reduced carbon emissions and air pollution from energy conversion are the major benefits of using RER. While we can enjoy the benefits of renewable energy resources (RER), there is an urgent need to reduce carbon emissions and focus on carbon capture, storage, and utilization.

Carbon capture (i.e., CO_2 capture) and storage (CCS) and carbon capture and utilization (CCU) are recognized as potential pathways to combat global climate change.[18] Chemical sciences advance the process of CO_2 capture and storage (CCS) through chemical absorption and polymeric membranes. Meanwhile, CO_2 capture and utilization (CCU) involves catalytic conversion to produce products for industries such as food and beverage, as well as chemical production (e.g., urea, methanol).[19] While CO_2 is a major contributor to total greenhouse gas emissions, methane (CH_4) is equally concerning for global warming. The conversion of methane (CH_4) to methanol (CH_3OH) is currently of both academic and industrial interest, given the abundance of CH_4 feedstock in nature. However, the activation of the C-H bond in CH_4 remains a challenge, and the development of both heterogeneous and homogeneous catalysts is ongoing. While Cu-containing zeolites show promise for the partial conversion of CH_4 to CH_3OH, further developments are needed to deploy them on an industrial scale.

Energy efficiency and behavioural changes are interconnected, with the latter influencing the former. Energy efficiency is essentially a measure of output relative to input, with a higher ratio indicating the success of any industrial or domestic process in benefiting the environment. Beginning with household practices, energy efficiency can be extended to the industrial scale through the implementation of appropriate measures. For instance, households can opt for LED bulbs for lighting, utilize thermostats to regulate home temperature, and conserve water resources by scraping dishes before loading them into the dishwasher. These practices are not only cost-effective but also promote energy efficiency. On an industrial scale, implementing advanced insulation, utilizing waste heat recovery systems, maintaining optimal temperatures, and minimizing hot water wastage can achieve similar results. If the primary stakeholders of the environment, namely Homo sapiens, begin to take action against global warming and climate change, collective efforts will reduce net carbon emissions. Each small step taken by individuals will one day contribute to the success of the Paris Agreement, adopted by 196 Parties at the UN Climate Change Conference (COP21) in Paris, France, on December 12, 2015, aimed at restoring the health of the Earth.[20]

Conclusion

The industrial and agricultural revolutions, along with human activities, contribute to excessive CO_2 emissions, resulting in global warming. Chemical sciences offer effective solutions to this issue by addressing CO_2 emissions through (CCU) and (CCS), producing hydrogen and hydrogen-based fuels as alternatives to TER, and reducing energy consumption through industrial electrification. In addition to chemical sciences, human actions toward the use of RER and efficient energy utilization also play a significant role. Lastly, it is essential to acknowledge the role of governments and policymakers in promoting technologies for the aforementioned sustainable practices. Collaborative effort is the key to development and sustainability.

Statement on use of AI

No AI technology was used to prepare the essay.

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Finalist

GHG emissions: confront, cut, and conquer for a sustainable future as there is no planet B

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Introduction

Climate change is not a distant threat; it is a crisis unfolding before our eyes, with devastating impacts on the environment, economy, and society. The global average temperature has already increased by about 1.1°C since the pre-industrial era, and without immediate action, it is projected to reach or exceed 1.5°C by 2030.[1,2] The Intergovernmental Panel on Climate Change (IPCC) warns that to address this threat, global greenhouse gas (GHG) emissions must be reduced by approximately 45% from 2010 levels by 2030 and reach net-zero by around 2050.[2]

It is therefore imperative to understand the source and cut them. Human activities, such as burning fossil fuels, deforestation, and industrial processes, are primarily responsible for the unprecedented rate of climate change. The burning of fossil fuels not only drives climate change but also depletes finite energy resources. As Robert Swan famously said, "The greatest threat to our planet is the belief that someone else will save it." It is crucial that we acknowledge this threat and take action.

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.

CO_2 accounts for about 76% of total global greenhouse gas (GHG) emissions, with methane (CH_4), nitrous oxide (N_2O), and other fluorinated gases contributing significantly as well.[5] Carbon Capture and Utilisation (CCU) technologies[6,7] can play a vital role in reducing GHG emissions by capturing and converting CO_2 into valuable products, thereby promoting sustainable development.

Governments, industries, and research institutions must collaborate to overcome the challenges facing CCU and unlock its full potential for a low-carbon economy.

Confronting the present: carbon capture and utilisation (CCU)

CCU involves capturing carbon dioxide (CO_2) emissions from industrial processes, power plants, and other point sources, and then utilizing or converting this captured CO_2, a relatively stable molecule, into valuable fuels and chemicals, thereby reducing greenhouse gas emissions and creating economic value (Figure 1). Catalysis can be used to convert harmful pollutants from industrial processes and vehicle emissions into less harmful substances. For example, catalytic converters in vehicles use platinum group metals as catalysts to convert carbon monoxide (CO), nitrogen oxides (NOx), and volatile organic compounds (VOCs) into CO_2, nitrogen, and water vapor.[8,9] CO_2 can then be converted into valuable products, such as fuels and chemicals. Nanomaterials are being explored for capturing and storing CO_2 from industrial processes. For example, metal-organic frameworks (MOFs) and porous carbon materials are used as adsorbents to capture CO_2, which can then be stored underground or converted into useful products through catalysis. Recent works have focused on thermocatalysis, electrocatalysis and photocatalysis for CO_2 reduction reactions.[10-12]

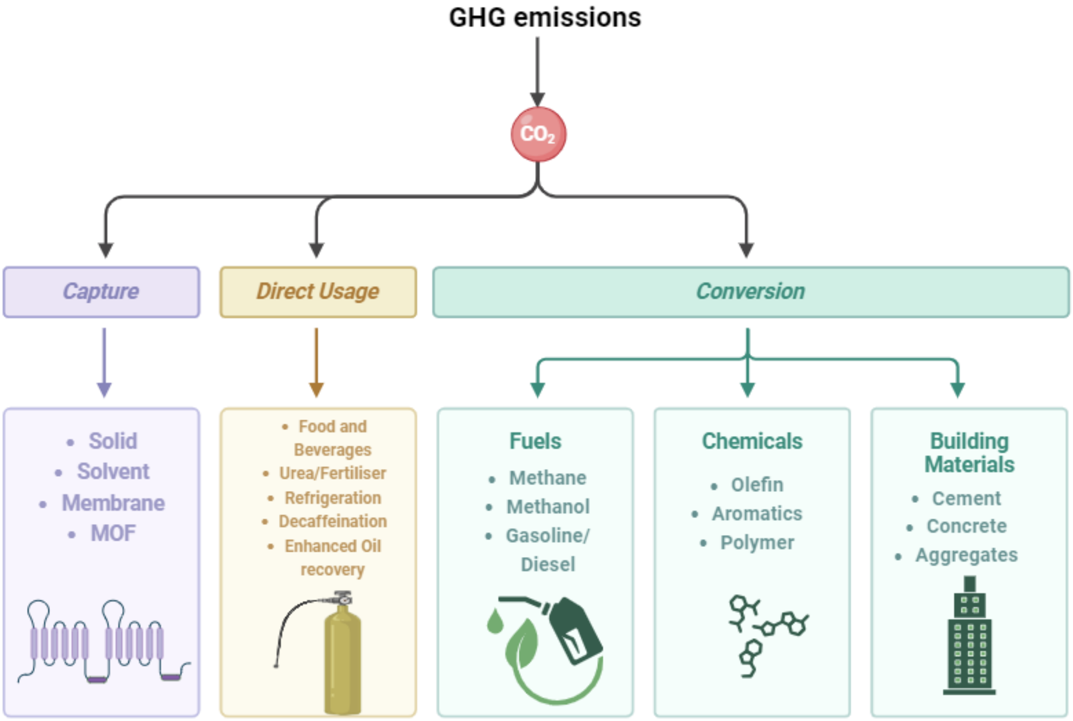

Figure 1 Carbon Capture and Utilisation (CCU) techniques

a) **Thermal Catalysis**: In the context of CCU, thermal catalysis can be used to convert CO_2 into various products, such as syngas (a mixture of hydrogen and carbon monoxide), methane, or higher hydrocarbons. One specific application of thermal catalysis involves the use of defected oxide supports with structural defects, such as oxygen vacancies, which can significantly influence their electronic structure and hence catalytic properties by promoting the adsorption and activation of CO_2 molecules.[13]

b) **Electrocatalysis**: It involves converting CO_2 molecules into products like carbon monoxide (CO), formic acid, methane, or ethylene by providing electric current. The electrocatalytic CO_2 reduction occurs under mild conditions using renewable electricity from sources like solar or wind. The electrocatalyst lowers the energy barrier, enabling efficient and selective conversion of CO_2 into specific products, based on market demand.

c) **Photocatalysis**: It involves directly utilizing the solar energy for CCU. It can be either photothermal or electron driven.

  i) Plasmonic catalysis: Plasmonic nanomaterials, typically metals such as gold or silver nanoparticles, exhibit surface plasmon resonance (SPR), which is the collective oscillation of free electrons in response to electric field of incident light. This phenomenon allows plasmonic materials to concentrating light energy at the catalytic sites in the form of hot-spots, making them excellent candidates for photocatalytic applications by polarizing the bonds of relatively inert CO_2. They also result in the generation of very high energy charge carriers also known as 'hot electrons' promoting the generation of reactive intermediates and accelerating reaction kinetics.[14,15]

  ii) Semi-conductor based photocatalysis: Semiconductor photocatalysts can convert CO_2 by using water as Hydrogen source as they can split water to produce hydrogen (H_2) under sunlight exposure. They facilitate the conversion of CO_2 into valuable products like carbon monoxide (CO) and methane (CH_4), as well as higher hydrocarbons and alcohols.[16]

These scientific advancements offer hope for a future where an inexpensive catalyst could convert CO_2 to hydrocarbon fuel using sunlight and seawater. This innovation could revolutionize the automobile industry by closing the carbon cycle, allowing vehicles to be fuelled with CO_2 and seawater instead of traditional fuels like petrol or diesel (Figure 2).

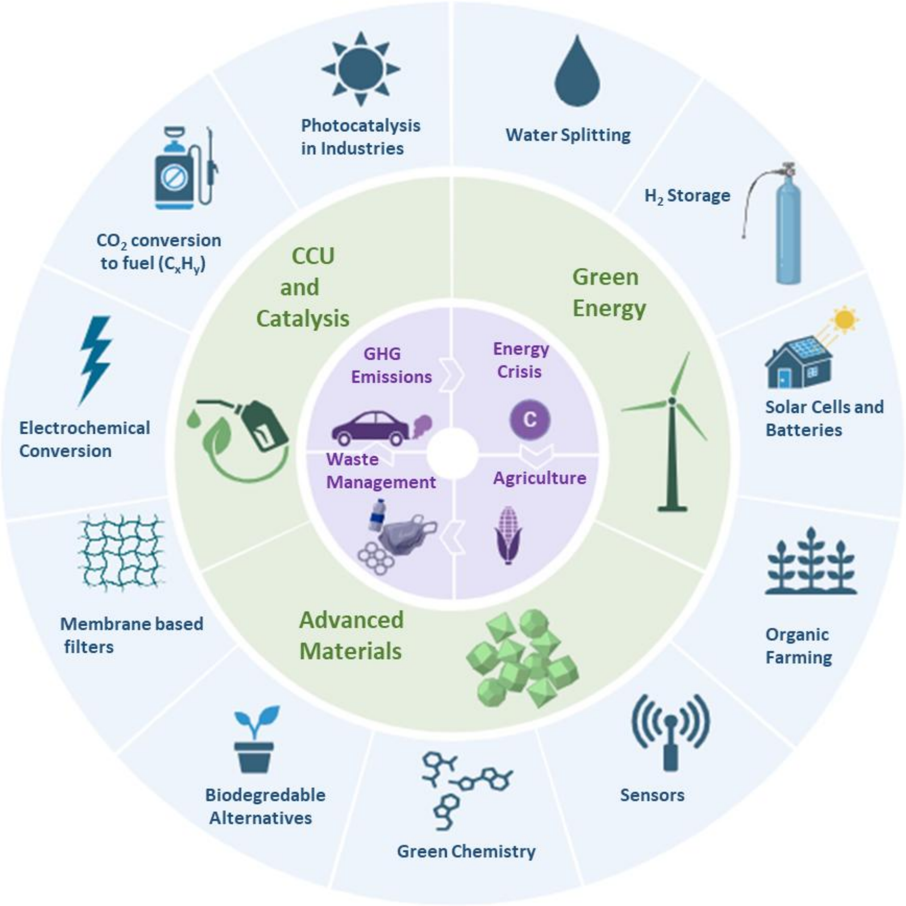

Figure 2 Role of chemical sciences in tackling environmental issues and promoting sustainable development

Cutting the source: replacing with green energy

a) Hydrogen economy:

The H_2 economy involves using hydrogen as a clean and sustainable energy carrier, which can be produced from renewable sources such as solar, wind, and hydropower through electrolysis. Steam reforming of natural gas is a common method for industrial hydrogen production but releases CO_2. Alternatives like water electrolysis, biomass gasification, and solar-driven thermochemical cycles are being developed for CO_2-free H_2 production.[17] To increase the energy density of H_2 for various applications, storage methods such as compression, liquefaction, and solid-state storage are being researched. Fuel cells offer a clean alternative to combustion engines and batteries, powering vehicles, buildings, and portable devices.

b) Solar energy storage

Nanomaterials are used in energy storage devices, such as batteries and supercapacitors, to improve their performance and efficiency. For example, researchers are developing nanostructured materials for lithium-ion batteries to enhance their energy density and cycle life, making them more suitable for renewable energy storage.[18] Thin-film solar cells, organic solar cells, and perovskite solar cells are emerging technologies that promise even higher efficiencies and lower costs, further driving the adoption of solar energy. Advancements in battery technology, such as solid-state batteries and flow batteries, offer higher energy density, faster charging capabilities, and improved safety, making them ideal for renewable energy storage applications. These technologies have already made a significant impact in reducing greenhouse gas emissions. Solar energy, for example, accounted for 3.3% of global electricity generation in 2020, avoiding over 2.6 billion metric tons of CO_2 emissions.[19]

Miscellaneous examples:

a) **Green chemistry**: Green chemistry can reduce GHG emissions through bio-based fuels, efficient catalysis based on renewable energy, solvent selection, and renewable feedstocks. It also promotes biodegradable polymers and chemical recycling for a sustainable future.

b) **Plastic waste management**: Advanced materials with enhanced efficiency of plastic recycling by breaking down plastics into molecular components for easier separation and recycling are being developed. Biodegradable alternatives to plastic can be developed, reducing the environmental impact of plastic waste by breaking down naturally.

c) **Development of sustainable agriculture practices**: Implementing practices such as controlled-release fertilizers, microbial bio stimulants, biopesticides, composting methods for waste management can advance organic farming practices, improve agricultural sustainability and reduce GHG emissions from agriculture sector.

d) **Environmental Monitoring**: Advanced Nano sensors can be used for environmental monitoring, including detecting pollutants and greenhouse gases in the atmosphere. These sensors help in understanding and mitigating the impacts of climate change.

Conquering for the future: policy making

Governments should set ambitious targets for increasing renewable energy in their mix, like the EU's goal of 32% by 2030, and heavily invest in the research and development R&D) of the same. Initiatives like carbon pricing, such as the EU ETS and Canada's carbon tax, can drive emission reductions. Phasing out fossil fuel subsidies can promote cleaner energy. Increased funding for CCU R&D and honouring Paris Agreement commitments are crucial. Germany and Japan have invested heavily in clean energy innovation: lobbying should be encouraged to educate other governments. Mobilizing private investment in green projects, like the Green Climate Fund, supports a sustainable economy. Investment in public transportation, electric vehicles, cycling infrastructure can reduce transport emissions. Specialised Awareness Programs can be arranged at agricultural universities to manage the crop waste to reduce the GHG emissions from burning. Initiatives like renewable energy generation, electric vehicle promotion, carbon pricing and clean cooking initiatives like biogas from India's 2024 budget demonstrate a commitment to promoting clean energy and reducing greenhouse gas emissions in line with international climate goals.

Conclusion

The urgent need to combat climate change requires a multifaceted approach that leverages the potential of chemical science, catalysis, hydrogen economy, energy storage, and other innovative technologies. By harnessing these advancements, we can mitigate greenhouse gas emissions, promote sustainable development, and pave the way for a more sustainable future. However, achieving these goals requires collaborative efforts from governments, industries, and research institutions worldwide. Through coordinated action and investment in clean energy technologies, we can effectively address the challenges of climate change and secure a more sustainable future for generations to come. Ultimately, “There is no planet B”, at least not yet.

Statement on use of AI

ChatGPT 4.0 has been used only to refine the language and limit the word count. No AI platform was used as search engine. The figures have been made using the Illustration Software: BioRender and no image-generative AI has been used.

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Finalist

Zeolites to the rescue: how Green Chemistry can capture carbon and power a sustainable future

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The challenges facing our planet are vast and interconnected.[1] Climate change, resource depletion, and pollution threaten the very fabric of our existence. However, amongst the seemingly unconquerable lies and doubts is a powerful tool for change: chemistry. By harnessing the principles of green chemistry and embracing innovative technologies, chemists can transform challenges into solutions for a sustainable future.

One pivotal area is the pursuit for clean energy. Our dependence on fossil fuels has created a greenhouse gas crisis.[2] Yet, carbon capture technologies offer a glimmer of hope.[3] Zeolites, a group of minerals with high surface area porous 3D networks of alumina and silica based molecular cages,[4] can be engineered to selectively trap carbon dioxide (CO_2) from industrial emissions.[5] By adjusting the size and charge of the pores within the zeolite framework, they can be tailored to preferentially capture CO_2 molecules, leaving other gases such as nitrogen (the main component of air) to pass through.[4] The targeted approach makes zeolites highly promising for capturing emissions from power plants and industrial facilities. These captured emissions can then be transformed and utilised. Compressing the CO_2 into stable minerals like quartz and burying them deep underground ensures it doesn't get released into the atmosphere.[6] An alternate application is taking the captured CO_2 and using it to enhance oil recovery, where CO_2 is injected into depleted oil fields to increase oil production.[7] While this approach has its own environmental considerations, it offers a temporary storage solution whilst better options are developed.

However, challenges remain. Whilst zeolites are efficient at capturing CO_2, the regeneration process of releasing the trapped gas, requires additional energy input.[8] Researchers are actively developing methods to optimise this process, such as low-grade heat or pressure swings.[9] Additionally, the large-scale implementation of zeolite-based carbon capture technologies requires further investigation on factors such as cost and scalability.

Despite these challenges, zeolites hold the potential for mitigating climate change. Their natural abundance, reusability, and ability to be tuned for specific applications makes them a frontrunner in the carbon capture field. By overcoming the current limitations and integrating them into use alongside renewable energy sources, a closed loop system can be created for better carbon management.

The synergy between carbon capture and renewable energy sources like biofuels is another promising avenue. Biofuels, derived from plant materials, offer a carbon-neutral alternative to fossil fuels.[10] However, their production can still contribute to CO_2 emissions.[11] By integrating carbon capture with biofuel production facilities, an improved system can be created, minimising net greenhouse gas emissions.[12]

The fight for a sustainable future extends beyond climate change. The agricultural sector plays a crucial role in the transition towards sustainability as traditional practises contribute towards environmental challenges such as soil degradation and biodiversity loss. Large-scale monoculture plantations used for biofuels can threaten biodiversity,[13] however, utilising non-food crops (such as switchgrass and miscanthus) and employing regenerative agricultural practices can promote biodiversity in these systems. Using fast growing crops that require less water and nutrients compared to traditional biofuels reduces the pressure on land resources and promotes biodiversity.[14] Additionally, the adoption of regenerative agricultural practises such as cover cropping improve soil health, increase carbon sequestration, and house a more diverse microbial soil environment, enhancing long-term agricultural productivity.

Traditional fertilisers contribute to nitrous oxide (N_2O) release into the atmosphere and result in ozone depletion. N_2O is a potent greenhouse gas, with a warming potential 265 times greater than CO_2. [15] The emissions stem primarily from synthetic nitrogen fertilisers, which are integral in modern agriculture. When the fertilisers are applied, not all of the nitrogen is readily absorbed by plants, the unused nitrogen seeps into the soil and undergoes biological processes that lead to the formation and release of N_2O.[16]

Bio-based pesticides and fertilisers, such as those that are zeolite based, can replace the more harmful synthetic counterparts. Zeolites offer an element of control when fertilising soil, as they can be used as carriers of nutrients and reduce the amount of nutrient loss, such as through leaching.[17] Leaching is the loss of water-soluble plant nutrients through rain and irrigation. It creates an issue when fertilising crops as not only can crops not grow strong root systems and flourish, but it also contributes to the rapid growth of algae in freshwater.[18]

On a similar note, zeolites, with their ability to capture specific molecules,[19] offer a potential solution for tackling microplastics polluting water sources. Researchers are exploring possible uses of zeolites for filtering microplastics from wastewaters before they enter the waterways, to protect marine life.[20]

Electrochemistry, the science of electrical energy and chemical reactions, paves the way for energy conversion without relying on fossil fuels.[21] Hydrogen fuel cells, which use hydrogen and oxygen to generate electricity, offer a clean and efficient alternative.[22] Further advancements in solar, wind, and geothermal energy can also contribute to a diversified, renewable energy grid. There are still challenges as whilst hydrogen fuel cell technology is rapidly advancing, the issue of widespread use is still under development.[23] With many chemical processes requiring heat and energy to fuel them, the problem of trying to replace fossil fuels remains. Despite these hurdles, electrochemistry is a rapidly growing path towards clean energy conversion, moving towards embracing more sustainable technologies. The solutions explored in this essay all directly contribute towards achieving the UN's sustainable goals. By mitigating climate change, a healthier planet is created. Sustainable biofuel production aligns with responsible consumption and production practises, whilst advancements in clean energy such as hydrogen fuel cells contribute to affordable and clean energy access.[24]

However, sustainability is not just about clean energy. It's about combining approaches that align with the UN's 17 Sustainable Development Goals. Green chemistry principles, emphasising the design of environmentally friendly chemical processes, are crucial. By minimising waste, maximising efficiency, and utilising renewable resources, chemists can create a more sustainable chemical industry.[24]

The journey towards a sustainable future requires not just scientific breakthroughs, but also bridging the gap between science, society, and policy. Open communication and collaboration can ensure that innovative chemical solutions are accessible and implemented effectively on a global scale. Local communities must be inspired to participate in the decision-making process and reap the benefits of these advancements. Most importantly, governments can incentivise research and development in green technologies, whilst encouraging international collaboration in tackling climate challenges.

The challenges we face are daunting, but the possibilities are endless. By embracing the power of green chemistry, carbon capture technologies, and renewable energy sources, we can create a future where chemistry acts as the catalyst for positive change.

Statement on use of AI

No AI technology was used to prepare the essay.

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Under-18 Finalist

Stalling climate change: reducing greenhouse gas emissions from energy conversion, agriculture and manufacturing

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"In the first place, there is general scientific agreement that the most likely manner in which mankind is influencing the global climate is through carbon dioxide release from the burning of fossil fuels," purportedly averred ExxonMobil scientist James Black to the oil-and-gas corporation's management committee in 1977.[1] It is currently the 2020s, and within the nearly fifty years since climate change and its palpable symptoms–melting ice-caps,[2] subsequent flooding,[3] wildfires and typhoons of heightened extremity[4,5] – rank amongst the most pressing of modern issues, resulting in international resolutions such as the UN's 17 Goals for Sustainable Development.[6] Methane and nitrous oxides have been added to the roster of heat-trapping greenhouse gases, and scientists of all disciplines are represented in the quest for more sustainable industries. Such is the breadth of the climate change discussion, that this essay shall focus only on methods by which the chemical sciences, in conjunction with governmental policies, may be used within sectors of energy production, agriculture and manufacturing to diminish the overall magnitude of greenhouse gases released.

When considering the challenge of mitigating greenhouse gas emissions, it becomes necessary to first address the vital role energy plays within all facets of society: Consumer Energy Solutions lists vast amounts of on-site energy consumption as the primary cause of emissions in industries,[7] and use of energy – in the form of oil, gas or electricity – is omnipresent in agriculture, from the manufacture of fertilisers to powering mechanical appliances.[8, 9] In a sense, it is the linchpin by which all other sectors are affixed: 'decarbonising' the conversion of energy would, consequently, dramatically reduce the quantity of greenhouse gases released by manufacturing, construction, farming, transport *etc.*

So where may chemical sciences find application within the sphere of low-carbon 'green energy'? Recent discussions have heavily centred on hydrogen energy storage, specifically 'green hydrogen' – the practice of electrolysing water into hydrogen and oxygen in order to convert electrical energy derived from renewable channels (wind, solar, oceanic) into chemical energy stored within hydrogen atoms. With an efficiency of roughly 38% when re-converted to electrical energy,[10] green hydrogen provides a solution to the persistent disadvantage of intermittent supply present in wind and solar energy, and can be transported with relative ease as liquid hydrogen (LH2), ammonia, methanol etc. A further advantage of green hydrogen when considered alongside the comparatively more widespread storage form of lithium-ion batteries is the lack of critical materials required: some experts have cautioned that demand for the metal – lithium batteries are also an indispensable component of digital devices and electrical vehicles – could result in shortages by 2030 under 'the most modest of demand projections'.[11] Unfortunately, the energy-intensive power-to-fuel-to-power processes involved with green hydrogen,[12] along with current high costs of production, are perceived as impractical by investors.[13] To facilitate the economic viability of green hydrogen as a fuel carrier, it is necessary for renewable energy itself to become more cheaply available, through governmental intervention in the form of subsidies, such as those issued by the Chinese government for its electric vehicle industry,[14] and in evolving existing technology to be cheaper and more efficient, this latter option especially being inseparable from the field of material sciences. Manufacturers of poly-silicon for use in photovoltaic devices have observed shifts away from the classical Siemens process to less costly alternatives and some solar energy developers are looking to halide perovskites as a high-efficiency (though currently less durable) replacement for silicon entirely.[15,16] These innovations and myriad others are made possible by the chemical sciences, and as a whole are instrumental in realising a future of sustainable energy, and therefore an ecologically sound society.

Excluding energy consumption, there exist various specific processes by which greenhouse gases may be generated within agriculture and manufacturing.

The United Nations Environment Programme and others deem livestock typically responsible for 32% of human methane emissions.[17] A sizable portion of this occurs specifically in the form of enteric methane, a by-product of enteric fermentation by microbes (archaea, bacteria) inhabiting the rumen of livestock such as cows and sheep. Cows in particular have been described as the leading agricultural source of greenhouse gas emissions worldwide, each animal expelling as much as 220 pounds of methane per annum.[18] With meat and dairy consumption on the rise internationally as living conditions improve and population increases,[19,20] a possible strategy to address this costly climate impact is the development of chemical supplements or additives compatible with cow feed that reduce the amount of methane produced. EU-approved supplement Bovaer contains active ingredient 3-nitrooxypropanol (3-NOP), which lowers enteric methane production through inhibiting the MCR enzymes within methanogens,[21] leading to reduction in emissions of up to 30-45% depending on the type of cattle.[22] Research into the use of ozone to aerate cow feed by Zhang *et al* approaches the issue in a different manner, utilising the potent oxidising agent to eliminate hypoxic conditions in which methanogenesis occurs. Results from *in vitro* experiments over ten days using ozone (from commercial ozonators) pumped into a buffer at 0.07 mg/L show a 15.4% decrease in overall gas production, 'most notably CH_4 production by 20.4%, and CH_4 gas concentration by 5.8%', without noticeable effect to other properties of the feed.[23] Naturally, in order to implement products such as Bovaer on a large scale – as well as to execute more research into novel solutions such as feed aeration *in vivo* – governments should communicate sufficiently with practitioners of the chemical and biochemical sciences to popularise sustainability projects and implement policies encouraging good practice, whether that be environmental taxation or methods such as the 1930s NRA 'blue eagle': a distinct symbol to indicate standards for agriculturalists and spread awareness amongst the general public. Currently, Bovaer is available in over thirty-five countries and is poised to become a key asset in the achievement of sustainability commitments by such organisations as the Global Dairy Platform and Global Roundtable for Sustainable Beef,[24] placing chemical sciences on the cutting edge of reducing greenhouse gas emissions in agricultural settings.

Aside from enteric methane, another concern in agricultural greenhouse gas emissions lies in the treatment of manure. Ammonia-containing faeces from sources such as poultry release nitrous oxides (greenhouse gases possessing a Global Warming Potential of 273 in comparison to carbon)[25]as a result of nitrification and denitrification, in addition to methane when broken down by decomposers under anaerobic conditions.[26] As an alternative to the disposal method of lagoons, wherein manure and other animal waste from farms is collected in low-oxygen basins,[27] studies have been made examining the potential of biomass-based thermochemical pyrolysis to simultaneously mitigate the release of aforementioned greenhouse gases whilst generating on-site power.[28] Analysis of biochar produced from pyrolysis of horse manure by Caro and Dahl suggests the suitability of using manure recycled in such a manner as soil amendments for crops, thereby creating a circular, zero-waste economy. [29]

Recycling is also a strategy encouraged for reducing production of greenhouse gases within manufacturing, as subtracting the process of procuring and transporting virgin materials significantly cuts down on energy consumed, whilst frameworks of 'Green Chemistry' continue to influence sustainable execution of typically GHG-yielding processes in both organic and inorganic chemical synthesis.[30]

Chemical sciences are invaluable in minimising and reversing the effects of climate change. Whether through remodelling how we obtain and store green energy, combatting the source and effects of livestock emissions or creating circular economies within manufacturing, it is patent that with adequate support from local and global administrations these technologies may yet secure a stable future for humanity.

Statement on use of AI

No Al technology was used to prepare the essay.

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Under-18 Finalist

Why 100% renewables does not mean carbon neutral

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Over the last 20 years, there has been significant scientific advancement and advocacy for renewable energy. Globally, renewable energy is the fastest growing energy source with renewable energy capacity growing by 50% in 2023 alone.[1] Renewable energy remains on track to account for more than 42% of global electricity generation in 2028 according to the International Energy Agency (IEA), unlocking the possibilities of achieving global tripling of renewable energy generation capacity goal set at COP28 in December 2023.[1] However, using 100% renewable energy does not equal carbon neutral energy, the ultimate goal of energy generation. On a life cycle basis, there is still significant CO_2 output from processes such as manufacturing, installation, and decommission of renewable sources (Figure 1). Thus, a holistic, system-based view provided through a life-cycle approach is key to decarbonising our environment and current mitigation strategies. The chemical sciences play a critical role not only in developing the solutions to the challenges of decarbonization, but also the responsibility of communicating accurate and reliable information to the public.

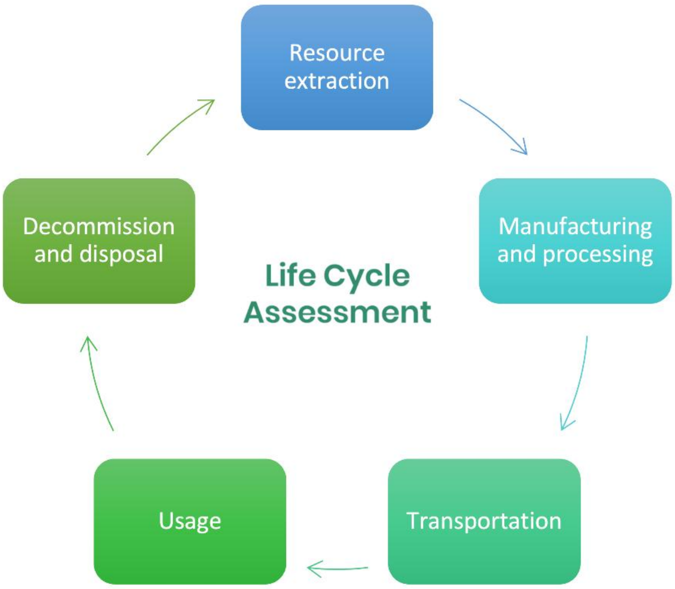

Figure. 1. Diagram showing typical stages of a life cycle assessment. The CO_2 output from each stage in this process should be evaluated to study the environmental impact of a process or product and the role of chemical sciences can be manifested through developing new intervention at each stage.

Significant CO_2 emissions are produced during the manufacturing of many renewable energy sources. In a 2019 study conducted by the Swedish Environmental Research Institute, researchers found that production of upstream battery materials contained the largest share of emissions at 59 kilograms of CO_2 equivalent per kilowatt-hour of battery capacity.[2] Batteries are one of the fastest growing source of energy storage, with the Energy Information Administration (EIA) expecting total battery storage to double in 2024 by adding 14.3 gigawatts (GW) to the existing 15.5 GW totalled at the end of 2023.[3] However, this will become problematic if no action is taken to reduce the CO_2 emission during manufacturing, as the demand for batteries are continuously rising. Another example of 'embedded' carbon emissions is the manufacturing of solar photovoltaic (PV) panels, where there is significant carbon emission associated with mono-crystalline PV at 2,560 kg CO_2 equivalent per kWp.[4,5] To reduce the embedded carbon in solar PV panels, the chemical sciences are key to discovering new materials that will achieve this and ongoing research on a cadmium-telluride based PV system suggests an over 60% decrease in embedded carbon compared to the mono-crystalline PV.[5]

The decommission of wind turbine blades, which are non-biodegradable, is another method in which renewable sources can have an indirect carbon output. Wind energy remains the world's leading renewable energy source, with total energy conversion more than all other renewable sources combined.[6] However, the turbine blades have an estimated lifespan of only 20 years, and researchers have predicted that by 2042 there will be more than 8.6 million tonnes of blades being decommissioned worldwide.[7] Researchers in Denmark are pioneering research into preventing this, by using chemistry to break down tough epoxy plastic which make up the blades and recycling the materials to produce future wind turbines.[8] Therefore, it is important to consider a wider, system view of energy generation, from manufacturing to disposal, with chemistry working in partnership with other disciplines to support decarbonisation.

Although renewable energy is becoming an increasingly dominant source of energy, non-renewable sources such as fossil fuels or coal remain highly profitable and remain the dominant energy source today. Therefore, the chemical sciences can also aid the decarbonisation of these sources, supporting the transition to renewable options. Chemists are utilising new strategies in carbon capture where the carbon captured is re-used in industrial processes by converting it into other products such as plastics, concrete or biofuel .[9] This approach improves the carbon output of non-renewable sources such as oil and coal, helping to reduce carbon emissions in all fields of energy conversion. An example of carbon capture, storage and utilisation (CCSU) in action is the coal-fired Schwarze Pumpe power station in Germany; the station captures nearly 95% of CO_2 released which is then used to make carbonated beverages (e.g. Coca-Cola) or sold to oil farms to increase yield of petroleum.[10] By injecting CO_2 into oil wells, it is possible to increase oil yield through a process named CO_2 Enhanced Oil Recovery (EOR).[11] Through CO_2 EOR, it is possible to offset the production of CO_2 when burning the oil, even injecting more CO_2 to the oil field than produced from burning offering a potential store of CO_2. Although CO_2 EOR currently operates on only 5% of the total US crude oil production,[12] it has been estimated that more than 90% of the world's oil reservoirs are potentially suitable for this technique.[13] The methods of decarbonisation for non-renewable sources are equally important to bridge the transition to a renewable energy source, and the chemical sciences provide novel techniques such as carbon capture and CO_2 EOR to support this.

Alternatively, it may be more effective to reduce net emissions of CO_2 than it is for net removal. Up to 3 tonnes of CO_2 emissions can be avoided for every 1 tonne of CO_2 used in the production of polycarbonate polyols.[14] Another avenue of research is the production of "green hydrogen" from the electrolysis of water using renewable energy compared to the conventional "brown hydrogen" generated by reforming methane and involving CO_2 emisisons.[15] However, current cost barriers and renewable energy supply sets challenges for large scale shift towards green hydrogen and competition with the inexpensive brown hydrogen.[15] To summarize, it is through both reduction of CO_2 emission and utilisation of CO_2 that will make decarbonisation successful. The chemical sciences offer novel strategies in both approaches, from developing more efficient catalysts to using carbon captured from coal power stations for carbonated beverages.

Not only do the chemical sciences have a role in developing ways to decarbonise energy conversion, but chemists also have an important role in communication of accurate scientific knowledge to companies and the wider public with regards to the efficiency of renewable sources and new methods of energy generation. By educating the public and society at large on renewable energy, people can make informed decisions about their energy providers and reduce misleading marketing which some of these providers utilise. A recent TV advert in 2022 by oil and gas giant Shell misleadingly suggested that low-carbon energy products made up a significant proportion of Shell's energy product, when in fact Shell disclosed emission of 1,377 million tonnes of CO_2 equivalents in 2020, ranking second in GHG emissions among the Big Oil companies worldwide.[16,17] Chemical scientists have a role in preventing and combatting the rise of "corporate greenwashing", where companies overstate their environmental friendliness.[16] At the UN Climate Conference (COP27) in 2022, the McKenna report outlines ten recommendations to improve corporate transparency and a zero tolerance attitude towards greenwashing.[18] Therefore, it is crucial for chemical scientists to increase society's scientific knowledge to pressurise companies such as Shell to take definitive action and reduce corporate greenwashing. Moreover, by educating the public and key stakeholders (investors, customers, governments etc.) on importance of decarbonisation and its effects on the environment will encourage further funding and more action to be taken. For example, this could mean imposing a carbon tax to penalise fossil fuels and brown hydrogen as well as incentivise the transition towards green hydrogen. Chemical scientists should also highlight the importance of a life-cycle approach to stakeholders and how it offers various pathways for carbon reduction, so a multifaceted approach is utilised.

Overall, although renewable sources are the next steps in achieving carbon-neutral energy production, we must consider the life-cycle analysis for these energy sources from manufacturing to decommission and the carbon emissions associated with these processes. Chemical science and technology pioneers the development of novel solutions to decarbonise the energy sources and in turn use cleaner, carbon-neutral energy in manufacturing industry. Scientists also have a fundamental role in communicating with society and improving the public's scientific literacy, encouraging corporate transparency in carbon emissions and guiding key stakeholders to areas of focus. Priority to be given to the most promising and least-developed options so early and effective adoption of a portfolio of techniques can be achieved.[12] It is through a holistic, interdisciplinary approach with chemists working with other fields together that will accelerate the road to decarbonisation and ultimately lead to long-term solutions. With chemists, scientists, and society all working together, achieving a 100% carbon neutral energy source is now closer than ever.

Statement on use of AI

No Al technology was used to prepare the essay.

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