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Chemical sciences: the key to a carbon-neutral future

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The year 2023 was the hottest ever recorded. As extreme weather events, such as droughts, floods, storms, and wildfires, are felt all over the world, the global population is personally exposed to climate change and is becoming increasingly aware to the consequences of unsustainably using the Earth's resources.

Climate change is mainly associated with the emission of carbon dioxide (CO_2) and other greenhouse gases (GHG), such as methane (CH_4) and nitrous oxide (N_2O), produced by anthropogenic activities.[1] The increase in global temperatures is related to the higher concentrations of these gases in the atmosphere, as these substances trap more heat in the Earth's atmosphere.[1,2] Higher temperatures result in warmer oceans, which intensify water evaporation and cause more frequent, severe, and prolonged heat waves and droughts, ultimately leading to heavy precipitation, intense wildfires, and extreme tropical storms.[2] Therefore, it is imperative to reduce GHG emissions and preserve the delicate climate balance that renders our planet a hospitable and thriving environment for all existing fauna and flora.

Energy production, industrial manufacturing, and agriculture account for the vast majority of global GHG emissions, emphasizing that our future depends on new solutions to transform these key sectors.[1] Owing to the wide plethora of innovative technologies offered across diverse scientific fields, the chemical sciences are pivotal for designing more circular and resource-efficient economic models that can reduce GHG emissions, fostering the transition towards a carbon-neutral future.

Global energy-related CO_2 emissions reached a new high of around 37.4 Gt in 2023.[3] However, without the expansion of clean energy technologies from 2019 to 2023, such as solar photovoltaics (PV), wind, nuclear, heat pumps, and electric cars, emissions could have tripled the 900

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Mt recorded.[3] Solar direct electricity-generating systems, particularly PV and photovoltaic-thermal setups, have gained popularity due to their abundance and recent advancements in enhancing electron transfer efficiency, conversion rates, and reducing manufacturing costs by incorporating nanomaterials, such as perovskite and carbon nanotubes, into solar cell design.[4,5] Photoelectrochemical cells are novel devices that can harness solar energy to drive chemical reactions, being capable of using efficient and low-cost photoelectrodes to convert sunlight into hydrogen (H_2) energy by splitting water molecules or reforming sacrificial organic compounds.[6] Hydrogen is the most promising alternative energy source because its only combustion product is water and is much more efficient than mainstream fuels (*i.e.*, the lower heating value of H_2 is 120 MJ kg^{-1}, whereas gasoline and methane (CH_4) are 44.5 and 50 MJ kg^{-1}, respectively).[6] This technology makes hydrogen transportable and storable (two of its biggest current drawbacks for widespread use), so it can be converted into electricity for mobile or stationary applications.[6] Despite these promising prospects, the cost for large-scale generation of H_2 using this approach is around 10$ per kg, making it economically unfeasible unless further research can make it a common and cost-effective fuel source.[6]

A major challenge in achieving a fully renewable-powered grid is the requirement for large energy storage due to the intermittency of the two most popular sources of energy (solar and wind power).[7] Nuclear energy has garnered attention as a sustainable energy source due to its ability to provide constant energy flow to the grid.[8] Advances in smaller and safer nuclear technologies, such as small modular reactors, can reduce the time, cost and environmental footprint of producing this type of renewable energy.[8] Additionally, nuclear energy can power CO_2 capture and sequestration technologies, enabling the simultaneous production of net-zero emission energy and the reduction of GHGs in the atmosphere.[8] Although nuclear waste management remains a significant concern, ongoing research seeks innovative solutions, such as glass–ceramic composites,[9] to remove, repurpose and/or stabilize these radioactive compounds. Nuclear energy is expected to play a crucial role in future energy mixes, alongside wind, solar, and hydroelectric energy, helping to ensure a consistent energy supply to the grid. Overall, chemical sciences are instrumental for designing novel technologies to improve renewable energy production and storage. Only by simultaneously developing high-storage capacity equipment, like improved batteries, flywheels, supercapacitors, and hydrogen fuel cells,[10] as well as more efficient renewable energy production processes, it will be possible to decarbonize energy production.

In the manufacturing sector, the implementation of green chemistry and engineering principles is critical to produce materials and chemicals using low-impact techniques, such as solvent-free synthesis and catalytic conversion.[11] To reduce GHG emissions, it is necessary to maximize process resource efficiency, eliminate and minimize hazards and pollution, and design holistic systems that embrace lifecycle thinking.[11] Key examples of such sustainable manufacturing processes are biorefineries and circular economy models. Biorefineries focus on integrating state-of-the-art technologies to convert biomass and agro-industrial residues into bio-based fuels, energy, and chemicals, maximizing the valorisation of raw materials and closing the loop of material flows.[12] Since biomass accumulates chemical energy in the form of carbohydrates by capturing CO_2 from the air during photosynthesis, this sustainable approach can also reduce the concentration of GHGs in the atmosphere.[13] The primary routes for biomass conversion are typically thermochemical and biological methods, encompassing processes such as combustion, pyrolysis, digestion and fermentation.[13] The implementation of such holistic techniques can further reduce GHG emissions using agro-forestry and food residues as renewable sources of biomass, producing energy and agrochemicals, such as biofertilizers and biocides. Hence, green chemistry and engineering processes can offer benefits to the energy, manufacturing, and agriculture sectors, reducing their reliance on non-ecological chemicals and compounds, while mitigating GHG emissions.

Concerning the rising GHG emissions linked to agriculture, primarily driven by the growing global population and consequently higher food demand, precision technologies are essential for resource optimization, minimal waste generation, and reduced environmental impact.[14,15] Precision agriculture (PA) can enhance crop yields by employing target inputs, such as fertilizers, biocides, and water, at the right place and time.[15] Artificial intelligence, nanotechnology, energy-efficient frameworks, and sensor networks, have recently been combined with chemical sciences for PA systems, making farming eco-friendly and cost-efficient.[16] Chemical analysis allows the monitoring of soil and nutrient management, with techniques such as crop rotation and cover cropping being used to promote soil health, enhance CO_2 sequestration, and reduce N_2O emissions from agricultural soils.[17] Furthermore, agricultural residues and biomass can be used to produce biofuels, biochemicals, and biomaterials, reducing reliance on fossil fuels, benefiting farmers economically, reducing GHG emissions, and promoting resource efficiency and circularity in agriculture.

Optimizing the management of CH_4 emissions from manure storage and treatment is also critical for achieving sustainable agricultural practices. Harnessing CH_4 as a bioenergy source in the form of biogas, capitalizes on the natural anaerobic fermentation of manure to produce electricity, heat, and/or fuel through combustion.[18] Additionally, the post-fermented manure serves as a biofertilizer to enhance crop growth, enabling the entire valorisation of this abundant by-product.

Despite all the promising solutions that chemical sciences provide to reduce GHG emissions, political change is essential for the rapid decarbonization of our world.[1] The adoption of such innovative technologies is only possible by implementing governmental regulations and directives which break the barriers that many stakeholders create between profitability and environmental sustainability.

Unfortunately, despite governmental organizations attempting to address the climate crisis by implementing well-intended strategies – such as the 2030 Sustainable Development Agenda with all countries in the United Nations (UN) signing a commitment to 17 Sustainable Development Goals (SDGs) in 2015 – they also support initiatives that jeopardize this sustainable transition. A clear example of this paradox are the funds (comprising billions (!) of dollars) that world governments receive every year by the UN Development Programme to produce and consume fossil fuels.[19] Such proposals promote environmentally unsustainable practices and discourage the implementation of more sustainable economic models, prioritizing economic growth over the social and environmental impact of these policies. To tackle climate change and environmental degradation, these programs must be exposed, and global organizations must present clear and objective strategies that shed light on the right direction and foster a transition towards a sustainable, resource-efficient, and competitive world.[20] Initiatives such as The European Green Deal are crucial to save lives, cut costs, and protect prosperity, ensuring that the risks and responsibilities inherent to each national, local, and regional entity concerning climate resilience, are well understood and addressed in the near future.[20] Harnessing the collective expertise of scientists, engineers, policymakers, and stakeholders can effectively accelerate this transition towards a low-carbon future and build a more resilient and sustainable society.

In the end, even with the diverse toolkit offered by chemical sciences to decarbonize energy production and mitigate GHG emissions across large-scale manufacturing and agriculture, the successful transition to a low-carbon future depends on you, me, and all the remaining people living with us in this blue sphere that we so tenderly call home. Chemical sciences can be the key to a carbon-neutral future, but it falls upon ALL OF US to oversee their effective implementation, in order to achieve a sustainable and prosperous world for both present and future generations.

Conflicts of interest

There are no conflicts of interest to declare.

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References

1 H. Ritchie, P. Rosado and M. Roser, *CO_2 and Greenhouse Gas Emissions*, Our World in Data, 2023, available at https://ourworldindata.org/co2-and-greenhouse-gas-emissions accessed March 26th, 2024.

2 *The Influence of Climate Change on Extreme Environmental Events*, National Geographic, Washington DC, 2023, available at https://education.nationalgeographic.org/resource/influence-climate-change-extreme-environmental-events/, accessed March 26th, 2024.

3 *CO_2 emissions in 2023*, International Energy Agency (IEA), Paris, 2024, available at https://www.iea.org/reports/co2-emissions-in-2023, accessed March 26th, 2024.

4 L. Wang, M. P. R. Teles, A. Arabkoohsar, et al., A holistic and state-of-the-art review of nanotechnology in solar cells, *Sustain. Energy Technol. Assessments*, 2022, **54**, 102864, DOI: 10.1016/j.seta.2022.102864.

5 T. Zhang, S. Iqbal, X. Y. Zhang, W. Wu, D. Su and H. Zhou, Recent advances in highly efficient organic-silicon hybrid solar cells, *Sol. Energy Mater. Sol. Cells*, 2020, **204**, 110245, DOI: 10.1016/j.solmat.2019.110245.

6 L. Clarizia, M. N. Nadagouda and D. D. Dionysiou, Recent advances and challenges of photoelectrochemical cells for hydrogen production, *Curr. Opin. Green Sustain. Chem.*, 2023, **41**, 100825, DOI: 10.1016/j.cogsc.2023.100825.

7 M. A. Opazo, Climate crisis: energy storage challenges in the transition to renewable energies, *RSC Sustainability*, 2023, **1**(7), 1602–1603, DOI: 10.1039/D3SU90038J.

8 J. Krūmiņš and M. Kļaviņš, Investigating the Potential of Nuclear Energy in Achieving a Carbon-Free Energy Future, *Energies*, 2023, **16**, 3612, DOI: 10.3390/en16093612.

9 Y. Zhang, L. Kong, M. Ionescu and D. J. Gregg, Current advances on titanate glass-ceramic composite materials as waste forms for actinide immobilization: A technical review, *J. Eur. Ceram. Soc.*, 2022, **42**, 1852–1876, DOI: 10.1016/j.jeurceramsoc.2021.12.077.

10 K. Guerra, R. Gutiérrez-Alvarez, O. J. Guerra and P. Haro, Opportunities for low-carbon generation and storage technologies to decarbonise the future power system, *Appl. Energy*, 2023, **336**, 120828, DOI: 10.1016/j.apenergy.2023.120828.

11 P. Anastas and N. Eghbali, Green Chemistry: Principles and Practice, *Chem. Soc. Rev.*, 2010, **39**, 301–312, DOI: 10.1039/B918763B.

12 A. B. Culaba, A. P. Mayol, J. L. G. San Juan, et al., Design of biorefineries towards carbon neutrality: A critical review, *Bioresour. Technol.*, 2023, **369**, 128256, DOI: 10.1016/j.biortech.2022.128256.

13 A. Garba, Biomass Conversion Technologies for Bioenergy Generation: An Introduction, in *Biotechnological Applications of Biomass*, ed. T. Peixoto, T. O. Basso and L. C. Basso, IntechOpen, Rijeka, 2020, ch. 1, DOI: 10.5772/intechopen.93669.

14 P. Kopeć, Climate Change—The Rise of Climate-Resilient Crops, *Plants*, 2024, **13**, 490, DOI: 10.3390/plants13040490.

15 W. Liu, X. F. Shao, C. H. Wu and P. Qiao, A systematic literature review on applications of information and communication technologies and blockchain technologies for precision agriculture development, *J. Clean. Prod.*, 2021, **298**, 126763, DOI: **10.1016/j.jclepro.2021.126763**.

16 R. K. Singh, R. Berkvens and M. Weyn, AgriFusion: An Architecture for IoT and Emerging Technologies Based on a Precision Agriculture Survey, *IEEE Access*, 2021, **9**, 136253–136283, DOI: **10.1109/ACCESS.2021.3116814**.

17 C. Wang, B. Amon, K. Schulz and B. Mehdi, Factors That Influence Nitrous Oxide Emissions from Agricultural Soils as Well as Their Representation in Simulation Models: A Review, *Agronomy*, 2021, **11**, 770, DOI: **10.3390/agronomy11040770**.

18 J. Köninger, E. Lugato, P. Panagos, M. Kochupillai, A. Orgiazzi and M. J. I. Briones, Manure management and soil biodiversity: Towards more sustainable food systems in the EU, *Agric. Syst.*, 2021, **194**, 103251, DOI: **10.1016/j.agsy.2021.103251**.

19 E. R. Newton, "We didn't start the fire": how the chemical sciences can steward the use of our Earth's chemical resources, *RSC Sustainability*, 2023, **1**, 1588–1590, DOI: **10.1039/D3SU90042H**.

20 *Key steps to manage climate risks to protect people and prosperity*, European Commission, Brussels, 2024, available at **https://commission.europa.eu/news/key-steps-manage-climate-risks-protect-people-and-prosperity-2024-03-12_en**, accessed March 26th, 2024.