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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 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 (CO₂) and other greenhouse gases (GHG), such as methane (CH₄) and nitrous oxide

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(N2O), produced by anthropogenic activities.1 The increase in global temperarelated 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 resourceefficient economic models that can reduce GHG emissions, fostering the transition towards a carbon-neutral future.

Global energy-related CO2 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 electricityceramic composites,9 to remove, repurgenerating systems, particularly PV and pose and/or stabilize these radioactive photovoltaic-thermal setups, have gained compounds. Nuclear energy is expected popularity due to their abundance and to play a crucial role in future energy recent advancements in enhancing elecmixes, alongside wind, solar, and hydrotron transfer efficiency, conversion rates, electric energy, helping to ensure and reducing manufacturing costs by a consistent energy supply to the grid. incorporating nanomaterials, such as Overall, chemical sciences are instruperovskite and carbon nanotubes, into mental for designing novel technologies solar cell design.4,5 Photoelectrochemical to improve renewable energy production cells are novel devices that can harness and storage. Only by simultaneously solar energy to drive chemical reactions, developing high-storage capacity equipbeing capable of using efficient and lowment, like improved batteries, flywheels, supercapacitors, and hydrogen fuel cost photoelectrodes to convert sunlight into hydrogen (H2) energy by splitting cells,10 as well as more efficient renewable water molecules or reforming sacrificial energy production processes, it will be organic compounds.6 Hydrogen is the to decarbonize possible energy most promising alternative energy source production. because its only combustion product is In the manufacturing sector, the water and is much more efficient than implementation of green chemistry and mainstream fuels (i.e., the lower heating engineering principles is critical to value of H₂ is 120 MJ kg⁻¹, whereas produce materials and chemicals using

and storable (two of its biggest current to maximize process resource efficiency, drawbacks for widespread use), so it can eliminate and minimize hazards and be converted into electricity for mobile or pollution, and design holistic systems stationary applications.6 Despite these that embrace lifecycle thinking.11 Key promising prospects, the cost for largeexamples of such sustainable scale generation of H2 using this are manufacturing processes approach is around 10\$ per kg, making it refineries and circular economy models. economically unfeasible unless further Biorefineries focus on integrating stateresearch can make it a common and costof-the-art technologies to effective fuel source.6 biomass and agro-industrial residues A major challenge in achieving a fully into bio-based fuels, energy, and chemrenewable-powered grid is the requireicals, maximizing the valorisation of raw ment for large energy storage due to the materials and closing the loop of material intermittency of the two most popular flows.12 Since biomass accumulates sources of energy (solar and wind chemical energy in the form of carbohydrates by capturing CO2 from the air power).7 Nuclear energy has garnered attention as a sustainable energy source during photosynthesis, this sustainable approach can also reduce the concentradue to its ability to provide constant energy flow to the grid.8 Advances in tion of GHGs in the atmosphere.13 The smaller and safer nuclear technologies, primary routes for biomass conversion such as small modular reactors, can are typically thermochemical and bioreduce the time, cost and environmental logical methods, encompassing footprint of producing this type of processes such as combustion, pyrolysis, renewable energy.8 Additionally, nuclear and fermentation.13 digestion energy can power CO2 capture and implementation of such holistic techsequestration technologies, enabling the niques can further reduce GHG emissimultaneous production of net-zero sions using agro-forestry and food emission energy and the reduction of residues as renewable sources GHGs in the atmosphere.8 Although biomass, producing energy and agronuclear waste management remains chemicals, such as biofertilizers and a significant concern, ongoing research biocides. Hence, green chemistry and seeks innovative solutions, such as glassengineering processes can offer benefits to the energy, manufacturing, and agriculture sectors, reducing their reliance on non-ecological chemicals 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 Artiintelligence, nanotechnology, energy-efficient frameworks, and sensor networks, have recently been combined with chemical sciences for PA systems, making farming eco-friendly and costefficient.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 CO2 sequestration, and reduce N2O 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 CH₄ emissions from manure storage and treatment is also critical for achieving sustainable agricultural practices. Harnessing CH₄ 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

gasoline and methane (CH₄) are 44.5 and

50 MJ kg⁻¹, respectively).6 This tech-

nology makes hydrogen transportable

profitability and environmental sustainability.

Unfortunately, despite governmental organizations attempting to address the climate crisis by implementing wellintended 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 each responsibilities inherent 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 lowcarbon 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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