International
Organization
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Chemical Sciences
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ROYAL SOCIETY
OF CHEMISTRY

YOUNG VOICES
IN THE CHEMICAL SCIENCES
FOR SUSTAINABILITY
2023

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

How can the chemical sciences lead the stewardship of the Earth's element resources?

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 2023
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Introduction

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

Through its action groups,[1] IOCD works to promote greater attention by the profession of chemistry to sustainability challenges. For example, the working group on Materials for Energy Conversion, Saving and Storage (MATECSS),[2] led by IOCD's Executive Director Federico Rosei, aims to expedite technology transfer in the areas defined by MATECSS by connecting experts from around the world with local scientists, engineers and students in low-and middle-income countries. It also aims to foster the development of low cost, adaptive technologies based on energy materials that fit within the paradigm of local-scale energy systems and that use local resources. IOCD's action group *Chemists for Sustainability* (C4S)[3] includes an international group of chemists who believe that chemistry and related sciences have indispensable roles to play in helping the world to achieve the UN 2030 Sustainable Development Goals. The group has served advocacy and think-tank roles through written articles, lectures at various fora and web materials.[4]

In 2023 the International Organization for Chemical Sciences in Development (IOCD) launched an annual Essay Competition, *Young Voices in the Chemical Sciences for Sustainability*.[5] 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 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, which is a leading voice for the chemical sciences and uses its influence to put sustainability in the spotlight, demonstrating how chemical science can provide solutions to the associated challenges.[6]

The 2023 IOCD Essay Competition, with the theme "*How can the chemical sciences lead the stewardship of the Earth's element resources?*", was open to entrants who were aged under 35 on the closing date, 31 March 2023.

From around 35 countries across the world, 87 applications were received by the closing date, with entrants' ages ranging from 12 to 34 (36 were aged under 20). 38 entrants stated they were female, 45 male and four did not say. In the first round, each essay was reviewed by at least three evaluators and entries with average scores above 66% were passed to an initial shortlist and subjected to screening by the RSC for plagiarism. 46 essays passed this screen and each was then further evaluated qualitatively and qualitatively by another three reviewers and the results passed to the IOCD judging panel. 21 essays were highly rated, based on their quality and relevance to the set topic. From within this group, six essays were chosen as Regional Winners, with regions being defined according to the World Bank geographic classification.[7]

The six essays designated as 2023 Regional Winners were published[8] in the October 2023 issue of *RSC Sustainability* as detailed below. In addition, each winning entrant received a prize of US$ 500 and a Winner's Certificate. While differing in their chosen entry points and areas of focus, the perspectives of the six Regional Winners share many commonalities. All recognise ways in which the chemical sciences are necessary in seeking solutions to the depletion of natural resources and the present and looming environmental crises that have resulted from the overuse and waste of these resources. They all call for more research and innovation that could lead to substitutes for scarce elements and polluting substances – but also recognise that science and technology offer only part of the solution. In addition to learning to work together more effectively across disciplines, scientists must actively engage with society and policy-makers to ensure that the most sustainable and environment-friendly technologies are adopted.

The 15 additional essays that were selected as Finalists in the 2023 competition are collected here and each of their authors also received a Finalist's Certificate. These essays provide further stimulating examples of the perspectives of young people on chemistry's role in stewarding the Earth's material resources. They consider the needs and opportunities for chemistry's engagement in resource stewardship from a variety of viewpoints, highlighting aspects of industry, research and education. They discuss challenges across the whole spectrum of the Periodic Table, highlight needs in relation to specific elements becoming scarce, such as the rare earths,. They provide examples regarding materials for agriculture, catalysis, digital technologies, energy production and storage (ranging from solar sources to better batteries to clean fuels such a green H_2) and they consider how to reduce waste and tackle pollution, especially that caused by (micro)plastics.. Circularity and applications of green and sustainable chemistry feature strongly, with the responsibility of chemists to provide innovative technical solutions being emphasised. Many of the essays consider the interfacing of chemistry's contributions with the essential roles that must be played by (1) policies and regulatory systems at both national and global levels and

(2) society at large, which needs awareness-building and encouragement to adopt less wasteful practices and to give support to measures urgently needed to tackle multiple environmental crises including climate change.

Overall, these essays from around the world provide an encouraging snapshot of the shifts that are underway in the field of chemistry and how it is perceived by young people studying, researching and working in the field. The knowledge-creating and utility-producing aspects of the discipline that have traditionally been seen as its key functions are increasingly being joined by an emergent new responsibility for chemistry practitioners that is understood to be urgent and of paramount importance. This is to help detect, avoid, minimise and counter harmful impacts on the environment that result from humankind's continually expanding use of natural resources, as well as to be good stewards of the resources themselves to maximise their continuing availability well into the future. These young voices show a heightened awareness of the importance of chemistry professionals entering the wider societal and policy debates, recognising that good technologies need to be attractive economically, politically and socially in order to be implemented.

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.

REFERENCES

1 What we do: current activities. International Organization for Chemical Sciences in Development, Namur, 2023. Available at: http://www.iocd.org/WhatWeDo/current.shtml

2 Materials for Energy Conversion, Saving and Storage (MATECSS). International Organization for Chemical Sciences in Development, Namur, 2023. Available at: http://www.iocd.org/WhatWeDo/Current/matecss.shtml

3. Chemists for Sustainability (C4S). International Organization for Chemical Sciences in Development, Namur, 2023. Available at: http://www.iocd.org/WhatWeDo/Current/sustainability.shtml

4. Publications, International Organization for Chemical Sciences in Development, Namur, 2023. Available at: http://www.iocd.org/WhatWeDo/publications.shtml

5. Global essay competition: Young Voices in the Chemical Sciences for Sustainability, *RSC Sustain.*, 2023,**1**, 10, https://doi.org/D2SU90002E

6. Our strategic approach to sustainability, Royal Society of Chemistry, London, 2023. Available at: https://www.rsc.org/policy-evidence-campaigns/environmental-sustainability/our-strategic-approach-to-sustainability/

7. World Bank Country and Lending Groups: Country Classification. World Bank, Washington DC, 2023. Available at: https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups

8. S. A. Matlin, F. Rosei, P. Lambin and L. Jin, The role of the chemical sciences in stewardship for sustainability, *RSC Sustainability*, 2023, https://doi.org/10.1039/d3su90041j

Regional Winners

Regional Winner
East Asia and Pacific

Chemical sciences, technological innovations, and resource circulation

Iris K. M. Yu
Department of Civil and Environmental Engineering, National University of Singapore, 1 Engineering Drive 2, 117576, Singapore

Iris Yu writes about the growing demands for metals and minerals and the critical question of how to sustainably acquire, use and recycle the Earth's available resources. She builds on the important aspect of resource circulation and presents a model involving a 'multi-loop resource nexus' to conserve and maximise the utility of available stocks and minimise the fraction lost to waste. This resource nexus provides many specific roles for the chemical sciences and highlights the potential synergies arising from the interactions among different circular economies.
Article at: *RSC Sustainability*, 2023, https://doi.org/10.1039/D3SU90037A

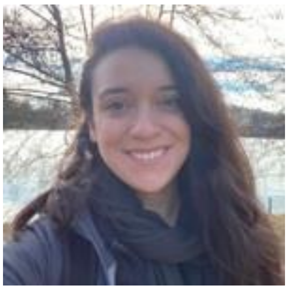
Regional Winner
Europe and Central Asia

"We didn't start the fire": how the chemical sciences can steward the use of our Earth's chemical resources

Eleanor R. Newton
School of Chemistry, College of Health and Science, University of Lincoln, Brayford Pool Campus, Lincoln, LN6 7TS, UK.

Eleanor Newton begins with the recognition of the growing demand for material resources and the accelerating speed at which useful, sometimes critical stocks are being depleted. Concluding that the chemical sciences have a stewardship responsibility whose goal must be to manage these resources in a sustainable way, she advances three over-arching approaches. These involve encouraging innovation (especially extending the capacities of upcycling and recycling technologies), promoting education and awareness (as well as for chemists, improving scientific literacy in society and helping educate the public on pressing environmental issues and the importance of chemistry and sustainability in their day-to-day lives), and ("probably most importantly") advocating for better government regulations.
Article at: *RSC Sustainability*, 2023, https://doi.org/10.1039/D3SU90042H

Regional Winner
Latin America and the Caribbean



Climate crisis: energy storage challenges in the transition to renewable energies

Mariel A. Opazo

Facultad de Ciencias Físicas y Matemáticas, Universidad de Chile, Santiago, Chile.

Mariel Opazo writes on the energy aspect of climate change, focusing on the overarching challenge of energy storage in the transition towards renewable energy technologies. Her introduction emphasises the danger of ignoring the interlinkages between different Sustainable Development Goals (SDGs) and highlights the importance of an integral approach through interdisciplinary research. The growing demand for large energy storage facilities and for batteries is driving higher demand for the extraction of Earth's minerals, especially lithium and rare earth elements, with mining having a wide range of environmental impacts. She reviews battery and other storage options and considers broader implications arising from mining and its impact, as well as the need for societal engagement in behavioural change and making choices in areas such as transport options and recycling.
Article at: *RSC Sustainability*, 2023, https://doi.org/10.1039/D3SU90038J

Regional Winner
North America

The urgent recognition of phosphate resource scarcity and pollution

Thibaut L. M. Martinon

Department of Chemistry, University of Minnesota Twin-Cities, Minneapolis, MN 55455, USA.

Thibaut Martinon writes on phosphate scarcity and pollution, opening with the quote that "for phosphorus, there is neither substitute nor replacement." He highlights the ways that profligate use of this unique resource as a fertilizer have led to its widespread dispersal, contaminating surface-level water bodies and creating a multifaceted threat. He stresses the stewardship duty to develop new strategies for mitigating the impending crisis by directing public policy, both at local levels and internationally – for example to remove phosphates from detergents and personal care products. The need for chemical innovation is also emphasised, for example involving alternatives to common synthetic fertilizers in the transition to a sustainable farming economy. The essay also addresses phosphate removal and recovery from surface-level water bodies and highlights the heavy uses of phosphate-based fertilizers in first-generation biofuels.
Article at: *RSC Sustainability*, 2023, https://doi.org/10.1039/D3SU90040A

Regional Winner
South Asia

The excellence of chemical science in achieving a sustainable world

Selvakumar Selvarasu
Department of Inorganic and Physical Chemistry, Indian Institute of Science, Bangalore, Karnataka, India. 560012

Selvakumar Selvarasu opens with recognition that, as well as chemical sciences and other areas of science and technology, social and political solutions are needed to address complex environmental challenges such as climate change caused by human behaviour. Scaling up carbon capture to remove atmospheric CO_2, employing both storage and utilization options, requires further exploitation. Examples include materials based on metal-organic frameworks that can capture CO_2 more effectively with lower energy requirement. The essay also covers waste and recycling, as well as alternative energy carriers and sources, including green H_2 and biomass. It ends with discussion of the importance of policy and its implementation in society and the need for people to learn from childhood onwards about problems and solutions related to sustainability.
Article at: *RSC Sustainability*, 2023, https://doi.org/10.1039/D3SU90043F

Regional Winner
Sub-Saharan Africa

Science – a chess game against time

Petra van der Merwe
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Petra van der Merwe uses a gaming analogy to frame her essay, noting how playing chess parallels the way scientists must approach impacts on the environment. An example traces the history of our understanding of greenhouse effects and global warming and uses this to introduce the next crisis, in which the efforts to tackle global warming by substitution of energy sources is in turn creating a shortage of critical raw materials. Details of the large and increasing demands for elements required for a single product – the smartphone – illustrate the argument for greater attention to conserving, recovering and cyclically reusing available materials. Her examples include new technologies such as the application of microfluidic processes in the mining sector and of flow processes in synthesis and in the recovery of valuable elements from waste. She concludes that "chemical scientists can only be true leaders in stewarding the sustainability of critical elements if they take ownership of the growing issue" and calls for more interdisciplinary collaboration.
Article at: *RSC Sustainability*, 2023, https://doi.org/10.1039/D3SU90039H

Finalist

The chemical industry and environmental stewardship: finding its footing in the net-zero agenda

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INTRODUCTION

The chemical sector has heavily aided in the modern transformation of our world. From the creation of the secondary (rechargeable) batteries that are significant for objectives revolving around sustainability and energy,[1] to playing a significant role in the implementation of silicon computer chips, oral contraceptives, catalytic converters and the recovery from the COVID-19 pandemic, no one can dispute how the sector has truly been at the epicentre of innovation.

With that stated, the chemical sector has been labelled *'not on track'* to net zero by the International Energy Agency (IEA).[2]

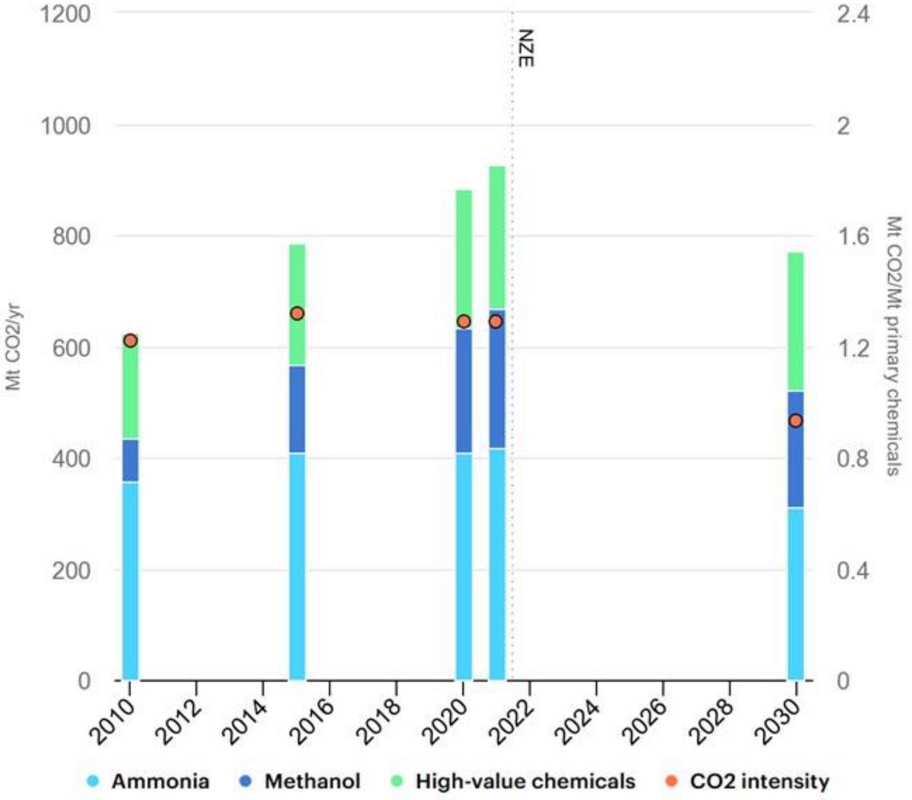

Figure 1 Direct CO_2 emissions from primary chemical production and CO_2 intensity in the Net Zero Scenario, 2000-2030 (IEA. Licence: CC BY 4.0, Ref 22)

CHEMICAL-BASED COMPANIES – ANY CHALLENGES?

When it comes to chemical sciences leading the stewardship of Earth's element resources, corporate figures play a key role and it is the responsibility of chemical companies' executives to ask themselves: *"Can we decarbonise our products in a way that we can continue to use that energy but we're not putting a strain on the environment?"*

Financing and innovation have been shown to be at the forefront of decarbonisation. However, with investors reluctant to invest in coal-fired power plants while there are requests for chemical companies to have their climate risks disclosed,[3] now is the time for companies to buckle down and strive towards monitoring and mitigating their emissions.

Supply chains and Scope 3 emissions: When it comes to the maintenance of growth, prosperity and a sustainable transition, the chemical industry is at the epicentre.[4] However, the industry faces some challenges when it comes to its supply chain(s), other than that of the lack of compliance,[5] with some of them being the industry's high energy utilisers arising from immense fossil fuels needs towards powering production.[6]

GOVERNMENTS: REGULATIONS & POLICIES – ANY CHALLENGES?

In the last decade, governments across the globe have embarked on numerous policies towards net zero, such as:

- Europe: EU Green Deal 2019, National CO_2 Levies
- North America: Commercial Frameworks, Supportive Climate (adoption driven in the USA by 45Q tax credits and in Canada by the prospects of carbon tax tripling by 2030)
- Middle East, Africa, APAC: Emission-reduction Incentives

At present, there is a mismatch in the scale between what is possible and matching the regulatory and financial structures to meet scale.[7a,b] Therefore, governments have to ensure they tread with caution because if they impose policy and regulatory regimes that are deemed overly demanding, it can prove to be highly detrimental to the industry, resulting in curtailed investments, energy shortages and high prices for consumers. That is exactly what is being witnessed across the world just now.

Definitely, much of what is happening across economies is linked to supply disruptions related to the conflict between Russia and Ukraine,[8] but it is also due to policies that were damaging over the past decade to the industry.[9]

Regardless of the policies implemented, it is crucial that there is a *just* transition because:

1. The less developed countries (those that cannot afford more expensive sources of energy) cannot be left behind
2. The countries that are highly reliant on the production and exports of fossil fuels cannot be left behind.

LOW-CARBON RENEWABLE TECHNOLOGIES – ANY CHALLENGES?

Prior to COP27, the IEA published a report in 2022 that examined the differences between 100% renewable energy targets and strategies where a business matches its annual electricity consumption with renewable sources on a global or regional basis.[10] When a business can state, *"We have this amount of kilowatt hours consumed and we are having this amount of kilowatt hours bought somewhere in the world,"* this usually takes a turn for the better, moving us closer to decarbonisation.

For the case of plastics, polycarbonate diol can be a better alternative as it can be made from CO_2. Carbon dioxide is a highly stable compound with tight atomic bonds,[11] however having it react with substances is far from simple. However, research has depended upon high temperatures and pressures towards driving the reaction which emits large amounts of CO_2.[12]

Other low-carbon solutions are decarbonised fuels, such as green hydrogen, and biofuels.

Hydrogen is a sustainable energy source that has received a lot of attention recently. One kilogram of hydrogen gas, which has a density of 0.089 kg/m^3, occupies more than 11 m^3 at room temperature and atmospheric pressure.[13] For instance, in the case of stationary hydrogen storage, the objective is to either, generally speaking, minimise the cost of delivered hydrogen through the balancing of supply and demand,[14] or to use it for backup reasons. Having said that, hydrogen storage has a unique collection of difficulties:

1. Conventional storage solutions are inclusive of compression/liquefaction (cooling it below -253°C).[15] It should be noted that these options have energy efficiency and substantial safety concerns paired with them.
2. Solid-state hydrogen has shown itself to be a more promising alternative.[16] Again, it should be noted that the alloys used, like that of the conventional $LaNi_5$, have extremely poor gravimetric hydrogen storage densities.
3. The delivery of high pure hydrogen is another difficulty to be highlighted. PEM (Polymer Electrode Membrane) fuel cells are among those that are sensitive to gas impurities[17] and require a very pure hydrogen feed for extended exposure.

HOW DOES THE CHEMICAL INDUSTRY DEMONSTRATE TO JURISDICTIONS AND GOVERNMENTS THAT THEY ARE DOING WHAT THEY CAN TO AID IN THEIR STEWARDSHIP OF THE EARTH'S RESOURCES?

Recommendations

1. Top pairings needed for a successful transition:
    - Top crisis management skills + co-ordinated policies
    - Bolder policies + capital allocations
    - Increased base land power + renewable energy sources
    - Energy security + price affordability
2. Achieving net-zero calls for chemical companies to follow a flow: from ***common practice*** to ***best practice*** to ***next practice***
    - Common Practice: Sustainability practices that are relatively standard across the industry
    - Best Practice: Sustainability practices that are pursued by only a handful of companies
    - Next Practice: Sustainability initiatives that are a few years away from maturity but will bear fruit for the industry

For example, a *'best practice'* could be making use of hydrocarbons from natural gas, a fuel which is clean at the point of consumption. In addition, undergoing the capturing and disposing of the CO_2 produced.

However, the chemical industry cannot embark on it alone. For a successful transition, the industry needs governments, investors and stakeholders to collaborate with and to be firmly and wholeheartedly on board. For example, climate finance institutions and chemical companies ought to have both short-term and five-year-term climate action plans that can be adequately implemented.

3. De-Risking Investments: Governments play a crucial role when it comes to de-risking investments. These could either be private investors-made government-guaranteed investments or government co-investments. They need to be deployed at scale to support the chemical industry, and other industries as well, as get closer to their respective net-zero objectives.
4. To omit the emission-inducing step of polycarbonate diol production, a catalyst can be used towards promoting the chemical reaction, this is required to encourage CO_2 to react with diol. A catalyst that has shown to be promising is cerium oxide.[18]
5. Due to the fact that the wind does not constantly blow and the sun does not constantly shine, it is even better if a chemical company can match wind and solar with base land dispatchable solutions like those of long-duration storage or advanced geothermal.
6. For corporate management: There are 3 activities management should embark on:
    - Destroy aspects of the inherited organisational administration that failed to be effective
    - Create new elements to have performance improved
    - Preserve aspects that perform well / that are effective

A management system has to be put in place and it has to mature as regulations mature, as assets age and as the facilities change. It is crucial to translate the corporate mandates, the corporate policies and the corporate goals into a project-level metric, a standardised definition, that every stakeholder is aligned on

For Scope 3 emissions: Measuring Scope 3 emissions is fundamental towards managing greenhouse gas (GHG)-related risks alongside opportunities.[19] This is where carbon accounting comes in. Carbon accounting calculates GHG emissions linked to goods' transportation, ultimately leading to the development of reduction strategies.

A great benefit of carbon accounting is it enables charterers towards meeting shareholder expectations as well as managing public perception

Through carbon accounting, the chemical industry will be able to:

- Benchmark: Having a baseline of emissions alongside a total carbon emissions target developed due to tracking emissions per journey and over. .[20]
- Report on Emissions: By setting, tracking and reporting any progress aimed at achieving net-zero targets via the use of real-time emissions data .[21] The disclosure can be in line with the Climate Disclosure Program

CONCLUSION

In order to protect earth's resources, the chemical industry has to undergo:

1. Governance: advocating for a net-zero enabling policy framework
2. Innovation: fast-tracking crucial innovations to commercial scale
3. Finance: de-risking of large-scale financial investments

Sustainability is not a linear problem. The chemical industry needs to think about sustainability in the way they think about safety. It is a continuous journey without a destination.

REFERENCES

1 S. H. Mauskopf (ed.), Chemical Sciences in the Modern World. Date: University of Pennsylvania Press, 1993. Available at: https://www.jstor.org/stable/j.ctv512t79

2 Chemicals, International Energy Agency, Paris, 2023. Available at: https://www.iea.org/reports/chemicals

3 Clean energy investing: global comparison of investment returns. A joint report by the International Energy Agency and the Centre for Climate Finance & Investment. Imperial College Business School, London, 21 March 2021. Available at: https://iea.blob.core.windows.net/assets/ef1d6b50-66a6-478c-990e-ee227e2dd89b/Clean_Energy_Investing_-_Global_Comparison_of_Investment_Returns.pdf

4 Measuring the emissions impact in the chemical sector: a guide on product carbon footprint. CEFIC, Brussels, 2023. Available at: https://cefic.org/media-corner/newsroom/measuring-the-emissions-impact-in-the-chemical-sector-a-guide-on-product-carbon-footprint/

5 R. Souza, M. S. Ide, G. Scur, W. L. Campos-Silva and S. Khorana. Sustainable procurement practices in the Brazilian chemical industry context. *Exacta*, 2020, 18(3), 583-602. https://doi.org/10.5585/exactaep.v18n3.10296

6 R. Vooradi, S. B. Anne, A. K. Tula, M. R. Eden and R. Gani. Energy and CO_2 management for chemical and related industries: issues, opportunities and challenges. *BMC Chemical Engineering*, 2019, 1, 1-17. https://doi.org/10.1186/s42480-019-0008-6

7 (a) M. Ulbrich, E. C. Eschenröder, B. Elser, M. H. Finn, N.Faisca, R. Sleep, A. Hensman, The chemical industry's road to net zero. Costs and opportunities of the EU Green Deal. Accenture/NexantECA, 2022. Available at: https://www.accenture.com/lu-en/insights/chemicals/eu-green-deal; (b) R. Tongia, Net zero carbon pledges have good intentions. but they are not enough, Brookings, 25 October 2021. Available at: https://www.brookings.edu/blog/planetpolicy/2021/10/25/net-zero-carbon-pledges-have-good-intentions-but-they-are-not-enough/

8 6 ways Russia's invasion of Ukraine has reshaped the energy world. World Economic Forum, Geneva, 8 November 2022. Available at: https://www.weforum.org/agenda/2022/11/russia-ukraine-invasion-global-energy-crisis/

9 Causes, effects and solutions to global energy crisis, Conserve Energy Future, 2022. Available at: https://www.conserve-energy-future.com/causes-and-solutions-to-the-global-energy-crisis.php

10 Executive summary — analysis, World Energy Outlook 2022, International Energy Agency, Paris, 2022. Available at: https://www.iea.org/reports/world-energy-outlook-2022/executive-summary

11 Carbon Dioxide. PubChem, National Library of Medicine, National Center For Biotechnology Information, Bethesda MD, 2023. https://pubchem.ncbi.nlm.nih.gov/compound/Carbon-dioxide

12 J. Li, H. Zhou and Y. Li. Synthesis of polycarbonate diol through the reaction of ethylene carbonate with diol. *Polym. Mater. Sci. Eng.* 28 (2012): 129-132.

13 The future of hydrogen. International Energy Agency, Paris, 2019. Available at: https://www.iea.org/reports/the-future-of-hydrogen

14 T. Saikia, S. Patil and A. Sultan, Hydrogen hydrate promoters for gas storage—a review. *Energies*, 2023, *16*(6), 2667. https://doi.org/10.3390/en16062667

15 Hydrogen delivery. US Department of Energy, Washington, DC, 2023. Available at: https://www.energy.gov/eere/fuelcells/hydrogen-delivery

16 E. Tegler. Could solid-state hydrogen storage be a serious alternative to batteries? *Popular Mechanics*, 28 April 2022. Available at: https://www.popularmechanics.com/science/a39679657/solid-state-hydrogen-storage-battery-alternative/

17 P. Pei, M. Wang, D. Chen, P. Ren and L. Zhang, Key technologies for polymer electrolyte membrane fuel cell systems fueled impure hydrogen. *Progress in Natural Science: Materials International*, 2020, *30*(6), 751-763. https://doi.org/10.1016/j.pnsc.2020.08.015

18 World's first "green" synthesis of plastics from CO_2 (2021) Asia Research News. Available at: https://www.asiaresearchnews.com/content/world%E2%80%99s-first-%E2%80%9Cgreen%E2%80%9D-synthesis-plastics-co2

19 How to tackle key sustainability challenges in the chemical industry. EcoVadis, 13 October 2020. Available at: https://resources.ecovadis.com/blog/how-to-tackle-key-sustainability-challenges-in-the-chemical-industry

20 B. Doda, Enabling carbon markets: carbon accounting, benchmarking and disclosure 2008-2010. London School of Economics Research Online, 2019. Available at: https://eprints.lse.ac.uk/101580/

21 Carbon accounting and reporting tools, World Wide Fund for Nature, Woking UK, April 2021. Available at: https://www.wwf.org.uk/sites/default/files/2021-04/Emission%20Possible%20Toolkit%20-%20Carbon%20Reporting%20Tools.pdf

22 IEA, Direct CO2 emissions from primary chemical production and CO2 intensity in the Net Zero Scenario, 2000-2030, IEA, Paris, updated 22 Sep 2022, Licence: CC BY 4.0. Available at: https://www.iea.org/data-and-statistics/charts/direct-co2-emissions-from-primary-chemical-production-and-co2-intensity-in-the-net-zero-scenario-2000-2030

Finalist

The chemical sciences as stewards of the earth's element resources

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INTRODUCTION

The finite nature of the Earth's element resources presents a significant challenge for society. The increasing demand for natural resources, driven by population growth, urbanization, and technological advancement, has led to resource scarcity and raised concerns over their sustainability.[1] As stewards of the Earth's resources, the chemical sciences have a crucial role to play in addressing the challenges of resource scarcity and promoting sustainable development.[2] In this article, we will explore how the chemical sciences can lead the stewardship of the Earth's element resources, reflecting on the intersection of science, society, and policy aspects.

RESOURCE SCARCITY AND ITS IMPLICATIONS

Resource scarcity is a global challenge that has significant implications for economic development, social well-being, and environmental sustainability. Elements, such as metals, minerals, and rare earth elements (REEs), are essential components of many products, including electronics, transportation, renewable energy, and healthcare.[3] However, their extraction and production are associated with negative environmental and social impacts, such as pollution, habitat destruction, and human rights violations. Moreover, the increasing demand for these elements is putting pressure on their availability and affordability, threatening the stability of global supply chains and economic growth.[4, 5]

THE CHEMICAL SCIENCES AS SOLUTION PROVIDERS

The chemical sciences can contribute to addressing the challenges of resource scarcity and promoting sustainable development by providing innovative solutions to reduce waste, increase efficiency, and develop alternative resources. Chemical engineers can design and optimize processes for resource extraction, processing, and manufacturing, using cleaner and more efficient technologies. Chemists can develop new materials and processes for resource recovery, recycling, and substitution, using abundant and environmentally friendly resources. Analytical chemists can develop methods and tools for resource characterization, mapping, and monitoring, supporting informed decision-making and resource management.[6] Moreover, interdisciplinary collaboration among scientists, engineers, policymakers, and stakeholders can facilitate the translation of scientific knowledge into real-world solutions, taking into account the economic, social, and environmental aspects of resource management.[7]

EXAMPLES OF INNOVATIVE SOLUTIONS

Several examples illustrate the potential of the chemical sciences as solution providers for resource stewardship. One example is the use of bioleaching to extract metals from low-grade ores, mine tailings, and electronic waste. Bioleaching is a biotechnology-based process that uses microorganisms to dissolve metals from solid substrates, converting them into soluble forms that can be easily recovered.[8] Its major and typical process is shown in the following **Figure 1**. Bioleaching is an environmentally friendly and cost-effective alternative to traditional mineral processing, reducing waste and energy consumption, and increasing metal recovery rates. Moreover, bioleaching can be tailored to different types of ores and wastes, making it a versatile technology for metal extraction.[9]

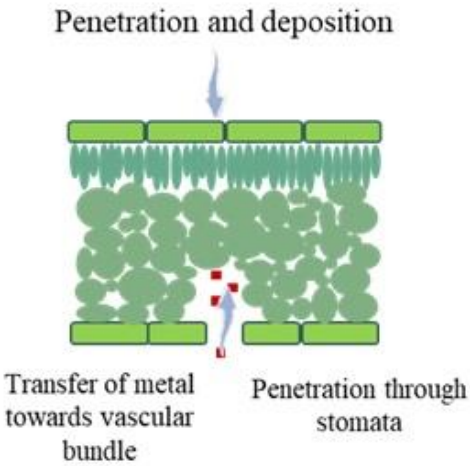

Figure 1 Schematic diagram of bioleaching process for removing metals.

Another example is the development of metal-organic frameworks (MOFs) for gas separation and storage. MOFs are a class of porous materials that consist of metal ions or clusters linked by organic ligands, forming a network of cages or channels. MOFs have high surface areas, tunable pore sizes, and selective adsorption properties, making them ideal candidates for gas separation and storage.[10] For instance, MOFs can be used to capture carbon dioxide from flue gases, reducing greenhouse gas emissions from power plants and other industrial processes. Moreover, MOFs can be used to store hydrogen, methane, and other fuels for energy applications, providing a safe and efficient alternative to conventional storage methods.[11] One of the Mo_2C nanoparticles is uniformly embedded in an N-doped chitosan porous carbon microsphere coated with graphene, forming a coating structure as shown in **Figure 2**, which was reported to significantly increase its electrocatalysis performance during the hydrogen evolution reactions and thus yield more hydrogen.[12]

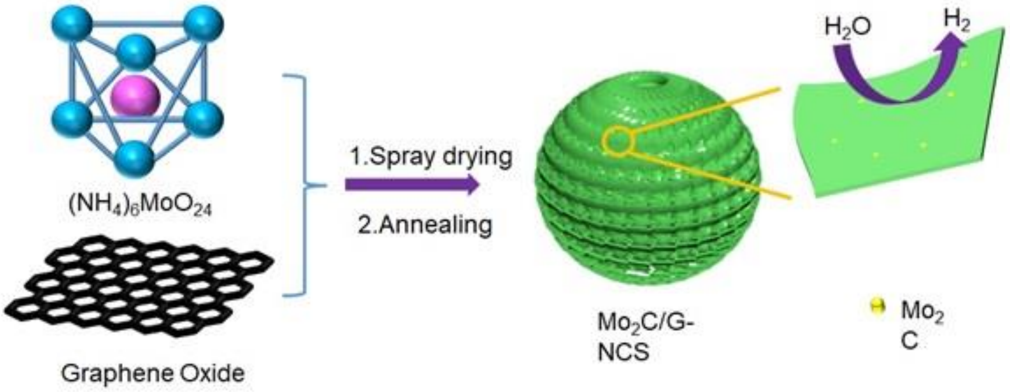

Figure 2 Schematic diagram of the forming of a certain MOF's coating structure

THE ROLE OF POLICY

The chemical sciences can also inform and influence policymaking for resource stewardship, providing evidence-based and science-informed solutions for sustainable development. Policymakers can use scientific knowledge and analytical tools to assess the environmental, social, and economic impacts of resource management decisions, and to develop policies that balance competing objectives and stakeholder interests. For example, policy-makers can promote circular economy principles, such as product design for recycling, extended producer responsibility, and waste reduction targets.[13]

Policymakers can also promote resource efficiency measures, such as eco-design, material substitution, and resource recovery, to reduce the environmental footprint of resource extraction and use. Moreover, policymakers can support research and development initiatives that advance scientific understanding and technological innovation for sustainable resource management, such as research into green chemistry and renewable energy.[14]

However, the implementation of sustainable resource management policies requires a multi-stakeholder approach, involving scientists, industry, civil society, and government. Stakeholder engagement can promote dialogue, trust, and collaboration, leading to better-informed and more effective policies. Moreover, stakeholder engagement can raise awareness and foster behavioural change, promoting sustainable consumption and production patterns and reducing the demand for scarce resources.[15]

THE GLOBAL DIMENSION OF RESOURCE STEWARDSHIP

Resource stewardship is a global issue that requires global cooperation and coordination. The challenges of resource scarcity and climate change affect all countries and regions, but their impacts and responsibilities are not distributed equally. Developing countries, in particular, face significant challenges in accessing and managing their natural resources, and in balancing economic development and environmental sustainability.[16] The chemical sciences can contribute to addressing the global dimension of resource stewardship by promoting international collaboration and capacity building, and by advocating for equity, diversity, and inclusion in science and technology.[17]

International collaboration can facilitate the exchange of knowledge, technology, and resources among countries and regions, promoting innovation and best practices in resource management. Capacity building can enhance the skills, competencies, and opportunities of scientists, engineers, and policymakers in developing countries, enabling them to contribute to sustainable resource management and address local and regional challenges.[18] Advocacy for equity, diversity, and inclusion in science and technology can promote social justice, human rights, and environmental sustainability, and ensure that the benefits and burdens of scientific and technological progress are shared fairly and inclusively.[19]

FUTURE DIRECTIONS

To address the challenges and limitations of resource stewardship, the chemical sciences can explore new directions and opportunities for research and innovation. One direction is the integration of digital technologies, such as artificial intelligence and machine learning, into resource management. Digital technologies can enable real-time monitoring and optimization of resource systems, improving efficiency, and reducing waste.[20] Moreover, digital technologies can enable better decision-making by providing more accurate and comprehensive data on resource availability, quality, and demand.

Another direction is the exploration of new frontiers in chemistry and materials science, such as nanotechnology and synthetic biology. Nanotechnology offers opportunities for developing new materials and processes with unique properties and functions, such as catalysis and sensing. Synthetic biology offers opportunities for designing and engineering biological systems for resource recovery and remediation, such as bioremediation of contaminated soils and waters.[21]

Moreover, the chemical sciences can explore opportunities for social innovation and entrepreneurship, such as community-based resource management and circular economy business models.[22] Social innovation and entrepreneurship can empower local communities and stakeholders to take an active role in resource management, promoting social and environmental sustainability. Circular economy business models can create new opportunities for value creation and economic growth while reducing waste and promoting resource efficiency.[23]

CONCLUSION

In conclusion, the finite nature of the Earth's element resources presents a significant challenge for society, requiring innovative and sustainable solutions to ensure their availability and affordability for future generations. The chemical sciences have a crucial role to play in addressing the challenges of resource scarcity and promoting sustainable development, providing innovative solutions and informing policymaking for resource stewardship. However, achieving sustainable resource management requires a multidisciplinary and multi-stakeholder approach, taking into account the economic, social, and environmental aspects of resource management. By exploring new directions and opportunities for research and innovation, we can overcome the challenges and limitations of resource stewardship and ensure a sustainable future for the Earth's element resources and the planet.

REFERENCES

1 Z. Ahmed, M. M. Asghar, M. N. Malik and K. Nawaz, *Resources Policy*, 2020, **67**, 101677. https://doi.org/10.1016/j.resourpol.2020.101677

2 A. P. M. Velenturf and P. Purnell, *Sustainability*, 2017, **9**, 1603. https://doi.org/10.3390/su9091603

3 A. R. Chakhmouradian and F. Wall, *Elements*, 2012, **8**, 333-340. https://doi.org/10.2113/gselements.8.5.333

4 V. Stratiotou Efstratiadis and N. Michailidis, *Metals*, 2022, **12**, 794. https://doi.org/10.3390/met12050794

5 D. H. Dang, K. A. Thompson, L. Ma, H. Q. Nguyen, S. T. Luu, M. T. N. Duong and A. Kernaghan, *Archives of Environmental Contamination and Toxicology*, 2021, **81**, 521-530. https://doi.org/10.1007/s00244-021-00867-7

6 T.-L. Chen, H. Kim, S.-Y. Pan, P.-C. Tseng, Y.-P. Lin and P.-C. Chiang, *Science of The Total Environment*, 2020, **716**, 136998. https://doi.org/10.1016/j.scitotenv.2020.136998

7 I. D. Graham, A. Kothari, C. McCutcheon, et al, on behalf of the Integrated Knowledge Translation Research Network Project, *Implementation Science*, 2018, **13**, 22. https://doi.org/10.1186/s13012-017-0700-y

8 R. Rathna and E. Nakkeeran, in *Current Developments in Biotechnology and Bioengineering*, eds. S. Varjani, A. Pandey, E. Gnansounou, S. K. Khanal and S. Raveendran, Elsevier, 2020, eBook ISBN: 9780444643223, pp. 437-458.

9 A. J. Whitworth, J. Vaughan, G. Southam, A. van der Ent, P. N. Nkrumah, X. Ma and A. Parbhakar-Fox, *Minerals Engineering*, 2022, **182**, 107537. https://doi.org/10.1016/j.mineng.2022.107537

10 M. Ahmadi, M. Ebrahimnia, M.-A. Shahbazi, R. Keçili and F. Ghorbani-Bidkorbeh, *J. Ind. Eng.Chem.*, 2022, **115**, 1-11. https://doi.org/10.1016/j.jiec.2022.07.047

11 H. Wang, Q.-L. Zhu, R. Zou and Q. Xu, *Chem*, 2017, **2**, 52-80. https://doi.org/10.1016/j.chempr.2016.12.002

12 H. Wei, Q. Xi, X. a. Chen, D. Guo, F. Ding, Z. Yang, S. Wang, J. Li and S. Huang, *Advanced Science*, 2018, **5**, 1700733. https://doi.org/10.1002/advs.20170073

13 N. Kunz, K. Mayers and L. N. Van Wassenhove, *California Management Review*, 2018, **60**, 45-70. Available at: https://cmr.berkeley.edu/search/articleDetail.aspx?article=5879

14 D. C. McKinley, A. J. Miller-Rushing, H. L. Ballard, R. Bonney, H. Brown et al , *Biological Conservation*, 2017, **208**, 15-28. https://doi.org/10.1016/j.biocon.2016.05.015

15 C.-W. Ki, S. M. Chong and J. E. Ha-Brookshire, *Corporate Social Responsibility and Environmental Management*, 2020, **27**, 2401-2424. https://doi.org/ 10.1002/csr.1970

16 Z. Jakab, D. Selbie, N. Squires, S. Mustafa and S. Saikat, *BMJ Global Health*, 2021, **6**, e006852. https://doi.org/10.1136/bmjgh-2021-006852

17 V. G. Zuin, I. Eilks, M. Elschami and K. Kümmerer, *Green Chemistry*, 2021, **23**, 1594-1608. https://doi.org/10.1039/D0GC03313H

18 A. S. Nizami, M. Rehan, M. Waqas, M. Naqvi, O. K. M. Ouda, K. Shahzad, R. Miandad, M. Z. Khan, M. Syamsiro, I. M. I. Ismail and D. Pant, *Bioresource Technology*, 2017, **241**, 1101-1117. https://doi.org/10.1016/j.biortech.2017.05.097

19 B. L. Montgomery, *Frontiers in Digital Humanities*, 2018, **5**, 22. 2018 | https://doi.org/10.3389/fdigh.2018.00022

20 M. Demartini, S. Evans and F. Tonelli, *Procedia Manufacturing*, 2019, **33**, 264-271. https://doi.org/10.1016/j.promfg.2019.04.032

21 T.-C. Tang, B. An, Y. Huang, S. Vasikaran, Y. Wang, X. Jiang, T. K. Lu and C. Zhong, *Nature Reviews Materials*, 2021, **6**, 332-350. https://doi.org/10.1038/s41578-020-00265-w

22 M. Charter and S. McLanaghan, Business models for a circular economy, in M. Charter and S. McLanaghan, Designing for a Circular Economy, Routledge, Abingdon-on-Thames UK, 2018, ISBN 9781138081017. https://doi.org/10.4324/9781315113067-9

23 S. Suriyankietkaew, K. Krittayaruangroj and N. Iamsawan, *Sustainability*, 2022, **14**, 5762. https://doi.org/10.3390/su14105762

Finalist

Cut the crap: a chemist's view on treatment of global issue of "plastic waste"!

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"Only human beings make waste that nature cannot digest", the quote reminds us of the serendipitous discovery, by Leo Hendrik Baekeland in 1907, of bakelite in search of synthetic plastics as an artificial replacement for shellac, a natural electric insulator.[1] Bakelite was formed by heating phenol and formaldehyde in a pressure vessel, resulting in flexible resin classified as a type of plastic "polyoxybenzylmethylenglycolanhydride". This material revolutionized the manufacturing industry and, today, plastics are used in a wide range of products, from toothbrushes to debit cards.[2–4] However, our dependence on plastics has also led to significant environmental issues, as they are not biodegradable and harm the ecosystem.[5]

From a chemistry perspective, plastics are a chemical class of polymers consisting of repetitive chains of small monomers (molecules).[6] Polyethene, polypropylene, polyvinyl chloride, polyethylene terephthalate and polystyrene are some common forms of plastics. On a toss of dice, despite enormous advantages, we are incredibly aware of the adverse effects of plastics on our health and environment. The blame lies with us being irresponsible creatures towards our mother earth. According to global data, less than 11% of plastic gets recycled in the United States and Canada out of 40 million tons of plastics, and less than 15% of it is utilized to produce electricity or heat.[5,7] In today's world, plastic waste is one of the major pollutants of solid waste, where initial steps of collection and washing before recycling make it a tedious and costly route to proceed. Therefore, people prefer dumping it free into land and oceans, which leads to a destructive environmental impact and a global issue.

We need to focus on various scientific and sustainable methods required to recycle plastics profitably, including modulation through mechanical stress and chemical structure. Sustainable discoveries considering the environment can be defined as "the needs of the present generation without compromising the ability of future generations to meet their own needs".[8] And as responsible citizens, we need to minimize utilization of plastics to compete for future needs, for instance, carrying biodegradable and re-useable clothing bags and opting for "no packaging" options. Additionally, landfills and incineration are other widely adopted options causing more environmental concerns. Recycling current plastics can potentially save substantial energy of up to 3.5 billion barrels of oil per year. However, it is not cost-effective and multiple types of plastics make this procedure complex. According to a recent survey, some plastics are recycled even less than 1%. Thus, strict legislation and policies should be followed for plastic recycling. However, government policies are deeply flawed and insufficient to save the environment.[5]

Recycling can be further classified into primary, secondary, tertiary, and quaternary. Primary recycling involves directly converting plastic waste to new products, whereas secondary involves mechanical stress in the presence of organic solvents to convert it to monomers. These traditional methods do not include many benefits and require high-cost consumption. Tertiary recycling, also termed chemical recycling, involves pyrolysis, hydrocracking, solvolysis, gasification (leads to the formation of syngas), catalytic cracking, catalytic depolymerization etc., where final products would be converted into valuable raw materials. Finally, quaternary recycling involves incinerating plastics to conserve energy from deterioration. This method decomposes seriously polluted waste using heat to burn complex compounds. [9]

Globally, all recent recycling technologies can be conducted under violent or mild conditions as shown in Figure 1. As the name suggests, violent situations involve harsh temperature and pressure conditions leading to efficient conversion (i.e., pyrolysis, hydrolysis, solvolysis and microwave catalysis) and valuable raw materials as products.[11] In contrast, mild conditions involving ambient temperature and pressure (photo/electro and bio-catalysis) positively affect the environment. Pyrolysis is an approach to convert longer-chain polymers to oligomers with shorter chains through heat and pressure without oxygen, leading to waste conversion towards oil, gas, and char. This method, also called potential thermal degradation, is used to treat mixed plastics, polyethene, polyethylene terephthalate, and complex plastic film waste.[9] Secondly, hydrolysis of plastics involves the treatment of low-density polyethylene, high-density polyethylene and polystyrene with bifunctional metal/acid catalysts, for instance, Pt-ZrO_2-S, Pt-ZrO_2-SO_4, $CoAl_2O_4$, etc. at a temperature greater than 500 K. Thirdly, solvolysis involves catalytic cross-alkane metathesis processes at relatively low temperature (300 – 500K) which further involves glycolysis, hydrolysis and methanolysis. Despite the difficulty in making a direct C-C bond, the nucleophilic attack on C=O in unsaturated polymers leads to conversion of bonds into C-O, and C-N, producing monomers and giving rise to purified products. Microwave catalysis involves heating through electromagnetic radiation, which makes the decomposition very fast with elevated temperatures and gives rise to a better quality of fuels as products, for instance, providing hydrogen production technology. On the down side, these routes require high temperature, energy consuming process, lesser selectivity and difficulty in understanding the complex mechanisms involving radicals and side reactions. Nowadays, catalytic consumption of plastic waste has attracted the global market to recycle plastics efficiently, involving acid/base catalysed degradation of polystyrene and other polymers under mild conditions. For instance, zeolites (ZSM-5, zeolite-β, and zeolite-Y families), SiO_2, and Al_2O_3 support polystyrene degradation at an elevated temperature of around 350 – 550 ºC.[10] The aromatic ring in the chain is protonated to form arenium intermediates, forming styrene/α-methylstyrene/benzene products. On the positive side, photo/electro/biocatalysis of plastics involves room temperature reactions, environmentally friendly performance, low energy consumption and high selectivity of products, attracting more attention.

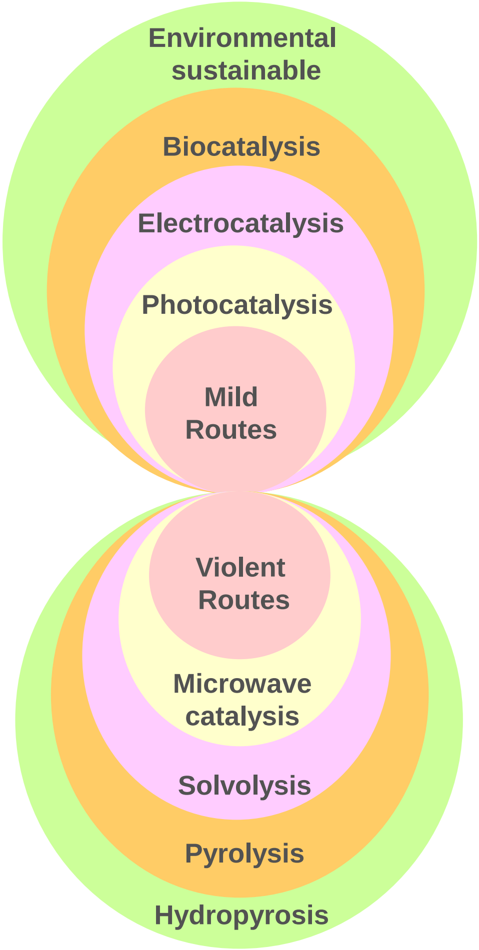

Figure 1 Strategies to deal with plastic waste (recycling routes)[9]

To promote clean, green, and sustainable technology, strategies under mild conditions are more promising for recycling as they leads to H_2 generation, CO_2 reduction and photocatalytic nitrogen fixation. Photocatalysis involves decomposing plastics under sunlight, involving free radicals such as hydroxyl and superoxide. For instance, polyethene is initially photo-oxidized into CO_2 through C-C bond cleavage with the help of O_2, hydroxyl and peroxide formation, which are used to reduce CO_2 and lead to the formation of useful molecules of carboxylic acid.[12] Since solar energy is a renewable resource and the reaction is conducted at standard temperature and pressure, photodegradation is the most promising method with minimum energy consumption. On the other hand, electrocatalysis involves consumption through externally applied voltage to convert plastic waste into hydrogen/oxygen evolution, CO_2 reduction and N_2 fixation in ambient conditions. The typical electrochemical cell involves oxidation and reduction reactions at the cathode and anode in the presence of an electrolyte. For instance, polyethene terephthalate is decomposed to ethylene glycol with the help of potassium diformate and terephthalic acid and hydrolysis and acid-assisted reactions.

Another sustainable consideration for recycling plastics is waste consumption by microorganisms under normal environmental conditions. In this category, organisms like arthropods, mollusks and annelids would consume plastics in their guts. Besides, microorganisms will cleave the bonds in plastics to attain valuable compounds. This is one of the most breakthrough categories of getting an eco-friendly solution to treat plastics, which still requires much improvement in enhancing efficiency. Yoshida et al. discovered a novel bacterium, *Ideonella sakaiensis* 201-F6, that produces two enzyes that hydrolyse polyethylene terephthalate (PET). The two-step chemical reaction of the acylation-deacylation process was conducted by special enzymes (Ser225 and His528) to convert plastic waste to ethylene glycol.[13]

Besides this, research on plasmonic electrons to treat waste plastic is searching for viable, sustainable options. We still need to explore ways to replace present plastics with recyclable polymeric materials along with an in-depth mechanism study before providing alternatives towards green chemistry. Though these tremendous efforts and a plethora of studies are well investigated, we are still facing challenges to simplify the treatment of waste disposal commercially. Therefore, it is highly advised that along with waste treatment, we should ban toxic plastics to prevent future crises. The governments of Canada and the United States need to regularise strict rules to create a national plastics strategy so that the goal of a “plastic-free environment by 2025” can be accomplished.

REFERENCES

1 Leo Hendrik Baekeland. Science History Institute, Philadelphia, 2023. Available at: https://www.sciencehistory.org/historical-profile/leo-hendrik-baekeland

2 S. Kumari Recent trends in omics-based enzyme discovery to combat global plastic waste crisis, *Biotechnol. Kiosk*, 2021, **3**(5), 4-12. https://doi.org/10.37756/bk.21.3.5.1.

3 T. Strong, Plastic heart, black box, iron cage: instrumental reason and the artificial heart experiment. *disClosure: A Journal of Social Theory*, 1996, **5**, 5. https://uknowledge.uky.edu/disclosure/vol5/iss1/54

4 F. Wicks, Plastic arts: the chemistry that has formed so many of the objects in our world traces its roots to an accidental discovery 100 years ago. *Mechanical Engineering-CIME* 2007, *129* (6), 44–47.

5 V. K. Manam, Plastic waste management: turning challenges into opportunities, Bharti Publications, New Delhi, 2022, ISBN: 978-93-91681-06-7

6 M. Burmeister, I. Eilks, An example of learning about plastics and their evaluation as a contribution to education for sustainable development in secondary school chemistry teaching. *Chem. Educ.n Res. Pract.,* 2012, **13**(2), 93–102, https://doi.org/10.1039/C1RP90067F

7 Canada’s plastic pollution problem. Environmental Defence, Toronto, 2023. Available at: https://environmentaldefence.ca/canadas-plastic-pollution-problem/

8 Sustainability, United Nations, New York, 2013. https://www.un.org/en/academic-impact/sustainability

9 K. Zheng, Y. Wu, Z. Hu, S. Wang, S. X. Jiao, J. Zhu, Y. Sun and Y. Xie, Progress and perspective for conversion of plastic wastes into valuable chemicals. *Chme. Soc. Rev.,* 2023, **52**, 8–29, https://doi.org/10.1039/D2CS00688J

10 C. Marquez, C. Martin, N. Linares and D. D. Vos, Catalytic routes towards polystyrene recycling. *Materials Horizons* 2023, **10,** 1625-1640. https://doi.org/10.1039/D2MH01215D

11 D. Chen, L. Yin, H. Wang and P. He, Pyrolysis technologies for municipal solid waste: a review. *Waste Management* 2014, **34** (12), 2466–2486. https://doi.org/10.1016/j.wasman.2014.08.004

12 V. Tournier, C. M. Topham, A. Gilles, B. David, C. Folgoas, et al,. An Engineered PET depolymerase to break down and recycle plastic bottles. *Nature* 2020, **580**(7802), 216–219, https://doi.org/10.1038/s41586-020-2149-4

13 S. Yoshida, K. Hiraga, T.Takehana, I. Taniguchi, H. Yamaji, Y. Maeda, K. Toyohara, K. Miyamoto, Y. Kimura, and K. Oda, a bacterium that degrades and assimilates poly(ethylene terephthalate). *Science* 2016, **351**(6278), 1196–1199. https://doi.org/10.1126/science.aad6359

Finalist

Defining chemical science-based guidelines to manage primary and secondary mineral resources in a sustainable way

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All materials present in our everyday life originate from the approximately 100 stable elements of the Periodic Table, whose amounts on Earth are finite.[1] Today, some elements face a high demand increase, especially those that are involved in energy transition technologies such as rare earths, Li, Fe, Co, Ni, Zn or Ag that are used for batteries, wind turbines or solar panels. This observation addresses several issues including the management of raw materials stocks (which are finite and not available everywhere on the globe) and the environmental impact associated with their extraction, elaboration and use. The latter should be lowered as much as possible in order to avoid crossing any of the nine planetary boundaries.[2]

Chemistry is the science of matter transformation, so it is involved in every step of materials creation: from raw materials extraction to synthesis, design and elaboration. Chemical sciences have therefore an important role to play in the management of materials resources and the community has the legitimacy to implement and lead actions aiming at promoting a sustainable use of the Earth's resources, in a circularity objective. Among possible actions, three are discussed in this essay, illustrated by examples of minerals from the semiconductors and energy technologies in Europe. Nevertheless, the efforts should be performed similarly for all domains of chemistry, since circularity concerns all Earth’s elements.

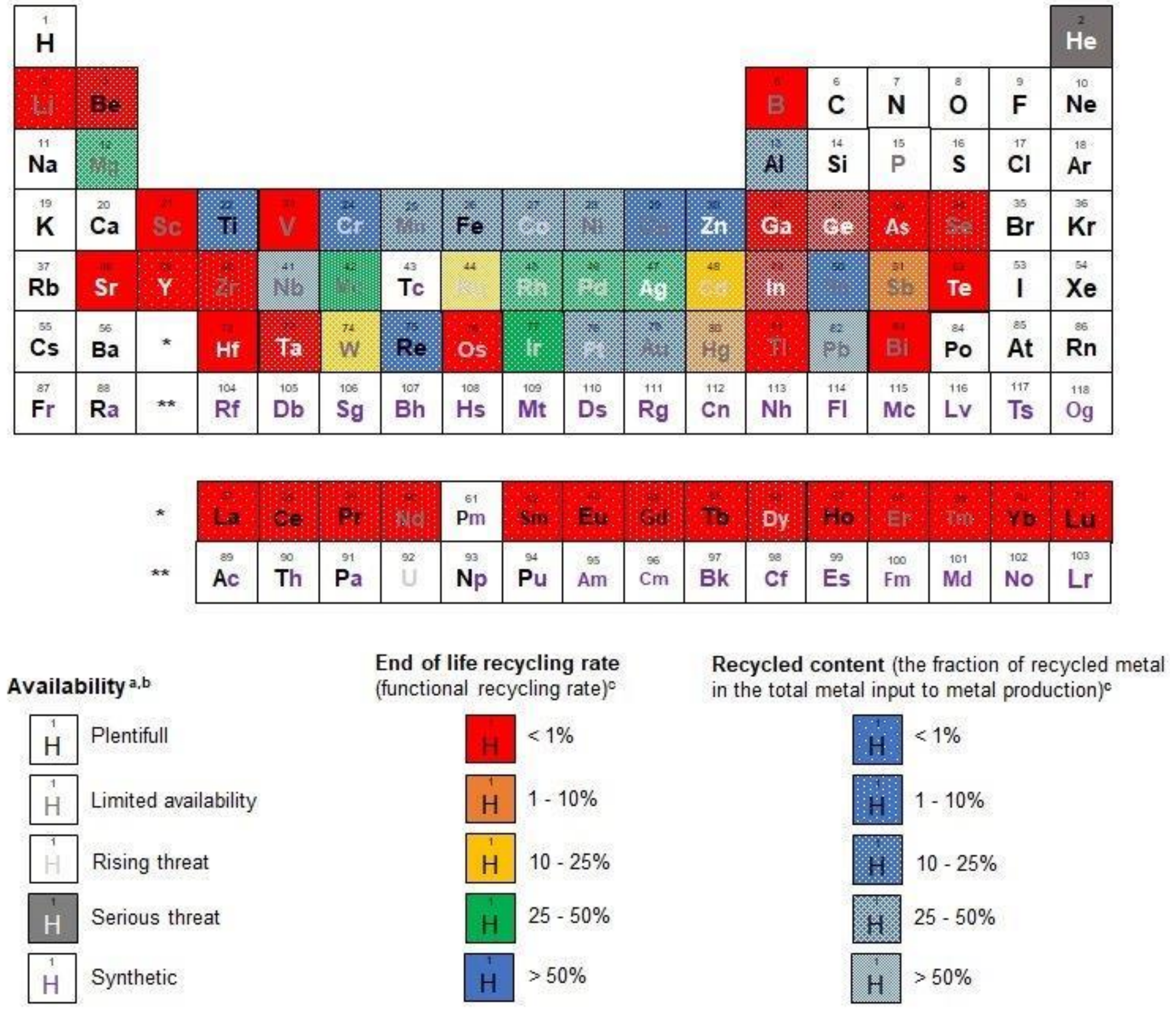
1. Promote, develop and make viable the recycling and use of “waste”

The Periodic Table depicted in **Figure 1** summarizes information about the availability of each element (label colour), their recycled rate (colour of the background) and the recycled content in new feedstock (dots density in the background).

The elements highlighted in red are those for which greater work should be done in order to find viable recycling solutions since less than 1% of the production is recycled. Recycling is challenging for several reasons: many devices contain a large number of different elements (at least 30 different elements can be found in a cell phone[1]), and developing a recycling process to qualitatively extract each of them might be difficult. The quantities of some elements may also be low, complicating their efficient and economically viable recovery. In Figure 1, the elements showing the higher recycling rate are either those present in large amounts (Pb in batteries) or with high value (Au in microelectronics).[3] Developing efficient recycling routes involves several fields working together. For instance, since 2018, Eramet (mining industry) together with Suez (collection and dismantling) and academic partners, developed a closed-loop recycling process of Li-ion batteries (ReLieVe project[4]), in order to recover Li, Co, Ni and Mn at a battery grade quality.

Figure 1 shows that few elements have a significant recycled content in new material production. In order to promote circularity, the position regarding “waste” elements needs to change. Scraps found in landfills or recovered for recycling should not be considered as waste anymore but as raw materials with equal value to the ones extracted from the ground. This also applies to the tailings, by-products and co-products generated during extraction or synthesis of materials, which are usually not considered because of their low concentration in valuable elements.[3] Studies regarding the recovery of high-quality Sn, Nb and Ta from the mining tailing of a closed tin mine in Penouta, Spain, using both pyrometallurgical and hydrometallurgical processes, are good examples of how mining “wastes” can serve as raw materials.[5,6]

It should be noted that the data used for Figure 1 are specific to metals and more information about nonmetals, especially all recyclable elements which do not feature a colour, could be helpful to get a more comprehensive view.



[a] EuChemS Periodic Table (2021)
[b] The periodic table's endangered elements, ACS Green Chemistry Institute, Chemistry Innovation Knowledge Transfer Network
[c] UNEP (2011) Recycling Rates of Metals – A Status Report, A Report of the Working Group on the Global Metal Flows to the International Resource Panel. Graedel, T.E.; Allwood, J.; Birat, J.-P.; Reck, B.K.; Sibley, S.F.; Sonnemann, G.; Buchert, M.; Hagelüken, C.

Figure 1 Periodic Table showing, for each element, its availability (label colour), recycling rate (background colour) and recycled content in production (white dots density).

2. Improve technology performances regarding resources

The performances addressed here relate to the stewardship of elements composing the devices, for example:

(a) Improve the efficiency per quantity of raw material
(b) Improve devices lifetime
(c) Lower the environmental impact of the extraction and manufacturing processes (regarding both planetary boundaries impact and safety).[7]

An illustration of these technology performance improvements is the recent breakthrough of LED lighting. Compared to the previous lighting technology, Compact Fluorescent Lamps (CFL), LEDs have a longer lifetime (40 – 50,000 hours compared to 10 – 25,000 hours) [8] leading to change being required less often and therefore consumption of less material. Moreover, the amount of rare earth (Y, Eu) contained in LED phosphor is 15 to 20 times smaller than that in CFL.[8] Finally, LEDs are more energy efficient since they almost do not feature energy-loss through heat compared to CFL. As a consequence, they consume less electricity, lowering their environmental impact. It should be noted that the latter parameter has a wider scope than energy consumption, by taking into account the whole product lifecycle and assessing its potential impacts on ecosystem, safety or greenhouse gas emissions.[7] For instance, the Product Environmental Footprint (PEF) method implemented by the EU Commission[9] aims at giving a common method to assess the life cycle environmental performance of products.

3. Help establish policies defining objectives for resource management

To ensure the previously described actions are implemented properly, objective-providing policies are needed. Policymakers would benefit from working together with the chemical sciences field in their elaboration by being given chemistry-based insights and guidelines. Below are some hypothetical objective examples derived from actions suggested in sections 1 and 2 above.

- For each element, reach a minimal recycled content percentage in the new production
- Set recycling norms for the creation of new products: for instance, a product could not be sold without having an already-established and tested recycling process or the design of the products should include facilitating the recycling process (by using as few different minerals as possible in the product, or mixing them as little as possible)
- For selected product groups, increase the products lifetime by a given percentage, or ensure a given lifetime
- For selected products groups, set a maximal environmental footprint based on the total product lifecycle environmental performance

The latter objectives would be built with the help of several tools and operations such as:

- The creation of working groups gathering experts from all concerned fields of a given sector to collaborate and discuss policies, based on scientific knowledge. For example, the EU Joint Research Center (JRC)[10] is the EU's science and knowledge service seeking independent scientific advice and support for EU policies. Chemists could be involved in field-specific working group creation, which is needed for all sectors to discuss all chemical elements/products.
- Setting up data resource management tools to constantly inventory the mineral resources present in landfills and in active or closed mines, to facilitate their management and show the possibilities offered by recycling. The EU Raw Materials Information System platform[11] or the Urban Mine Data Knowledge Platform[12] are examples of EU initiatives to source and monitor data about mineral resources.
- Developing and spreading tools to estimate the environmental footprint of a product, a process or a company and make it easily accessible so that it would be widely used. Transparency in their utilization and results would also be essential, so as to concern all actors of the sectors and call the attention of the general public. The EU PEF method has been mentioned before, but other tools like Total Material Requirement (TMR),[13] or absolute environmental sustainability assessment (AESA)[14] also exist.

It should finally be noted that policies regarding Earth elements stewardship already exist or are being elaborated, like the EU Raw Materials Initiative aiming at ensuring a fair and sustainable supply of raw materials as well as efficient resource and supply of secondary raw materials through recycling.[15] The EU Commission has also defined a list of "critical raw material" (CRM)[15] which includes the elements shown in **Figure 1** as "less than plentiful" in addition to Be, Si, Ti and some minerals: natural graphite, coal, rubber or bauxite. The policies would however benefit from being implemented at a larger scale with quantified targets validated by all concerned sectors.

It is today recognized that circularity cannot be obtained via the above-listed means, which can only lower the environmental changes our planet faces.[16] The actions described need to be accompanied by an auto-limitation of the chemical sciences, that would encourage the diminution of production (and therefore consumption), crucial not to cross any more planetary boundaries. This cannot be achieved by the chemical field alone, but the community could be among the first to initiate this transition, which implies a change in our society's operation: placing respect for the environment as the first driver of choices instead of economics and growth.

REFERENCES

1 S. A. Matlin, G. Mehta, H. Hopf, A. Krief. The periodic table of the chemical elements and sustainable development. *European Journal of Inorganic Chemistry*, 2019**, 39-40**, 4170-4173, https://doi.org/10.1002/ejic.201801409

2 J. Rockström, W. Steffen, K. Noone et al. A safe operating space for humanity. *Nature*, 2009, **461**, 472–475. https://doi.org/10.1038/461472a

3 T. E. Graedel, J. Allwood, J.-P. Birat, B. K. Reck, S. F. Sibley, G. Sonnemann, M. Buchert and C. Hagelüken. Recycling Rates of Metals: A Status Report, A Report of the Working Group on the Global Metal Flows to the International Resource Panel, *UNEP*, 2011. Available at: https://wedocs.unep.org/bitstream/handle/20.500.11822/8702/Recycling_Metals.pdf?sequence=1&isAllowed=y

4 ReLieVe project of the European Union/EIT, 2020-2021. Available at: https://eitrawmaterials.eu/project/relieve/

5 O. Rodríguez, F. J. Alguacil, E. E. Baquero, I. García-Díaz, P. Fernández, B. Sotillo and F. A. López. Recovery of niobium and tantalum by solvent extraction from Sn-Ta-Nb mining tailings. *RSC Advances*, 2020, **10**(36), 21406–21412,. https://doi.org/10.1039/d0ra03331f

6 F. A. López, I. García-Díaz, O. R. Largo, F. G. Polonio and T. Llorens. Recovery and purification of tin from tailings from the Penouta Sn-Ta-Nb deposit. *Minerals*, 2018, 8(1): 20. https://doi.org/10.3390/min8010020

7 Designing safe and sustainable products requires a new approach for chemicals, European Environment Agency, 2021, Doc: TH-AM-20-029-EN-Q, ISBN 978-92-9480-349, https://doi.org/10.2800/055747

8 A. Rollat. Comment satisfaire les besoins en matières premières critiques? L'exemples des terres rares. Collège de France Colloque on "Ressources minérales et développement durable: des mutations pour préparer l'avenir", June 4th 2015. Available at: https://www.college-de-france.fr/fr/agenda/colloque/ressources-minerales-et-developpement-durable-des-mutations-pour-preparer-avenir/comment-satisfaire-les-besoins-en-matieres-premieres-critiques-exemple-des-terres-rares

9 L. Zampori and R. Pant. Suggestions for updating the Product Environmental Footprint (PEF) method, EUR 29682 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-00654-1, https://doi.org/10.2760/424613, JRC115959.

10 Science for policy, European Commission Joint Research Centre, 2023. Available at: https://joint-research-centre.ec.europa.eu

11 RMIS – Raw Materials Information System, European Commission, Brussels, 2023. Available at: https://rmis.jrc.ec.europa.eu

12 Urban Mine Knowledge Data Platform, ProSUM 2023. Available at: https://www.prosumproject.eu/urban-mine-knowledge-data-platform

13 T. Watari, B. C. McLellan, D. Giurco, E. Dominish, E. Yamasue and K. Nansai, Total material requirement for the global energy transition to 2050: A focus on transport and electricity. *Resources, Conservation and Recycling*, 2019, **148**: 91-103. https://doi.org/10.1016/j.resconrec.2019.05.015

14 V. Tulus, J. Pérez-Ramírez and G. Guillén-Gosálbez. Planetary metrics for the absolute environmental sustainability assessment of chemicals. *Green Chem.*, 2021, **23**(24): 9881-9893. https://doi.org/10.1039/d1gc02623b

15 Report on Critical Raw Materials in the Circular Economy, European Commission, Brussels, 2018. https://doi.org/10.2873/167813

16 G. Mehta, S. E. Cornell, A. Krief, H. Hopf and S. A. Matlin. A shared future: chemistry's engagement is essential for resilience of people and planet. *Royal Society Open Science*, 9(4), https://doi.org/10.1098/rsos.212004

Finalist

A chemist's vision for the future

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It has been said that mathematics is the language we use to describe the universe. If this is true, then chemistry is the universe. Everything around us exists because of chemistry, from the cells that make us to our morning coffee. From the water, we bathe into the precious metals that compose our mobile phones and laptops. Everything we use in modern society comes from natural resources. While we take most of these things for granted, imagining life on Earth 100 years ago is a difficult task. What has been accomplished in a relatively short period, such as the past century, is remarkable. Sadly, not all changes have been beneficial.

This past century has also seen the co-occurrence of consumerism, fossil fuel consumption, waste generation, and pollution all increase at alarming rates. The by-products of existing in modern society contribute to the defining crisis of our time. The current gross consumerism and production era has irreversibly depleted the Earth's natural resources. Although some resources like water and air are renewable, others, like fossil fuels, are not, and once they are gone, they are gone forever.

The energy we rely on to power buildings, homes, factories, and transportation and to produce products like electronics and cars relies on minerals and metals harvested from the Earth's natural resources. Even industries not producing physical products depend on infrastructure and energy created via natural resources. In a little over a century, we are exhausting resources that have taken the Earth 250 million years to produce. Burning these fuels is the primary driver of climate change resulting in devastating effects like the release of greenhouse gases (GHGs), melting glaciers, drought, famines, and ocean acidification. In 2019, over 80% of our energy came from fossil fuels (coal, oil, and gas).[1] If we continue to exhaust our precious resources at this rate, they will reach critical levels in the next 50 years.[2]

If things were not bad enough, add the burden of resource shortages on global economics. Increased fuel costs drive inflation, and the threat of a worldwide recession looms greater than ever. In addition, energy cost increases promote significant wealth transfers from consumers to producers, further widening the inequality gap. These inequalities, increased scarcity, and resource competition create an environment that cultivates social unrest, political tensions, and conflict. As is often the case, the poorest and most vulnerable citizens are most likely to suffer. This kind of economic disruption has been seen most recently with the Russian invasion of Ukraine. This war highlights the necessity of a shift from our current state, where a minority of countries supply the world's fuel, to low-carbon energy sources which can be installed at local levels. With predicted gas supply shortages, we are on the cusp of entering an era of energy poverty. Preserving life as we know it relies on carefully managing our precious resources.

Although these issues are troubling, a better future for all is within our reach. The universal nature of chemistry provides the ability to cross borders and connect science and technology with communities and governments worldwide. Imagine a sustainable world powered by circular economies. Biofuels would replace fossil fuels. Plastics would be biodegradable, raw materials would be made with alternatives to petroleum, and transport would be electrical. Water would be safe to drink, and nobody would be hungry. Medical treatments and vaccines would be cheap and accessible for all.

This kind of world is not just a pipedream but one that is possible through science. While chemistry is the science of the unseen, its impact can certainly be felt in every aspect of society. The chemical sciences are the underpinning for all modern society and fundamental to advancing fields such as medicine, materials, sustainable energy, food production, agriculture, and the environment. Recent advances in research and technology demonstrate the ability of chemistry to provide real solutions to the most pertinent issues currently faced by mankind.

A plan for sustainability will rely on systematic changes necessitating business and government collaborations backed by science. In 2015 The United Nations published the 17 Sustainable Development Goals (SDGs).[3] These goals provide us with a blueprint guide of where we should focus our research. As chemists, we can impact all 17 goals (Figure 1) by generating knowledge, assessing the latest data and trends and bridging the communication gap between policymakers and communities. The development of clean technologies, sustainable materials manufacturing, and the clever use and reuse of resources will create efficient, circular economies.

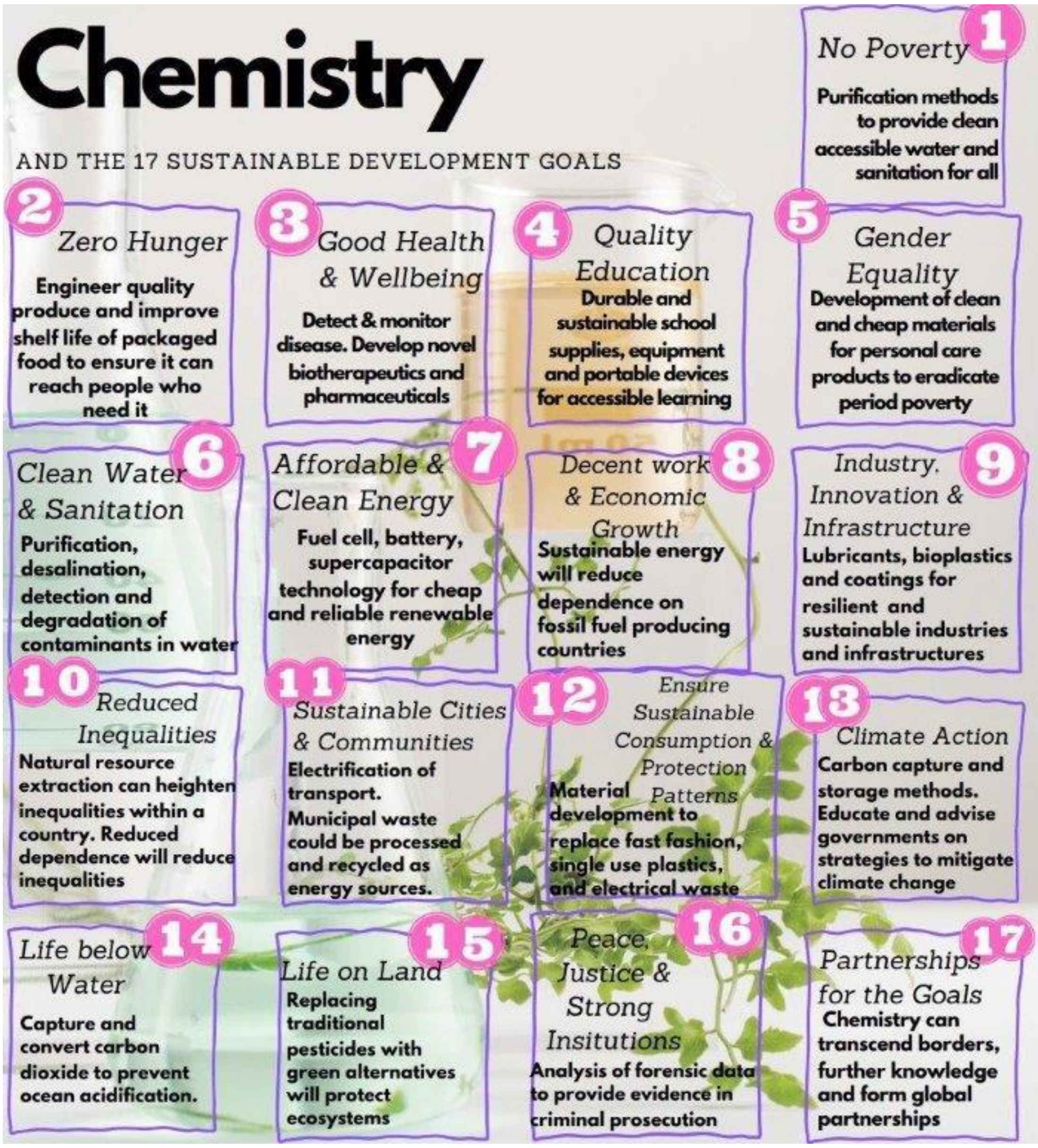

Figure 1 Ways in which chemistry can impact each of the 17 Sustainable Development Goals

Energy needs to be cheap and readily available to save our resources for future generations, and chemistry is at the forefront of the advancement of these clean technologies. Progress is underway with harnessing the power of renewables such as hydropower, solar, and wind to provide us with energy. We can further improve these sources by addressing intermittency issues using technology such as hydrogen-based fuel cells. Recent research in this area has focused on developing sustainable materials to catalyze processes such as water-splitting.[4] We can then use surplus wind and solar-generated energy in conjunction with these electrocatalysts to split water into hydrogen and oxygen via electrolysis. Fuel cells can then be employed to convert this hydrogen back into electricity. The by-product of this entire process is simply water, providing clean, sustainable technology. The introduction of policies and tax credits in the EU and the US further solidifies the necessity of transition to electrification. Fuel cell technology can provide a cheap and reliable source of heat and energy that could also be used locally. This would undoubtedly improve the lives of the over 770 million people without electricity worldwide.[5]

Biomass can also provide a clean fuel source and could help decrease GHG emissions. Biomass is made from plants and animals and provides an attractive alternative to fossil fuels.[6] These fuels can be produced by readily replenished carbon sources such as trees, agriculture, and food and waste residues. These sources undergo simple chemical processes such as fermentation and distillation to provide the resulting fuel. For example, Switchgrass is a resilient native plant species found in the Americas and can produce large amounts of biomass in the form of cellulosic ethanol. This alcohol is made via the degradation of cellulose found in the plant into its most basic components, and fermentation occurs by adding yeast. Switchgrass needs little fertilizer and is also resistant to droughts creating a harmonious cycle whereby vast amounts of biomass can be formed from a simple plant species in conjunction with a simple chemical process. Reduced chemical treatment and irrigation results in reduced energy input. If that was not attractive enough, we could even use one of the process's by-products, lignin, as fuel!

Ideas such as these highlight the importance of utilizing well-established fundamental chemistry to address issues highlighted in the SDG goals. Biomass such as seaweed can also be used to create a natural alternative to petroleum-based plastics.[7] Bioplastics are organic polymeric compounds isolated from living organisms such as plants or bacteria or made chemically from biological raw materials. These compounds can be functionalized and manipulated to finetune or provide desirable properties and can be used in product manufacturing, food packaging, clothing, toys, and even medical dressings.[8]

Switching use from traditional plastics to biodegradable plastics will minimize landfills and the detrimental effects on our oceans. Further, the development of eco-friendly nanomaterials can also help mitigate such stresses. Polysaccharide-derived catalysts, such as starch and chitosan-based materials, can remove harmful pollutants such as pharmaceuticals, dyes, and pesticides from our oceans.[9]

Preserving our natural resources is a time-sensitive task, and we should draw inspiration from the unprecedented focus and collaboration seen among scientists during the COVID-19 pandemic. The pandemic highlighted the necessity of communication and partnerships with scientists, governments and communities to achieve a common goal. We must continue this period of momentum and knowledge dissemination. Indeed, collaboration combined with the imagination and resourcefulness inherent to humans will ensure we as Chemists can continue to find innovative solutions to safeguard our precious resources for future generations.

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REFERENCES

1 H. Ritchie, P. Rosado and M. Roser. Fossil Fuels, Our World in Data, 2022. Available at: https://ourworldindata.org/fossil-fuels

2 S. Shafiee and E. Topal. When will fossil fuel reserves be diminished? *Energy Policy,* 2009, 37, 181-189. https://doi.org/10.1016/j.enpol.2008.08.016

3 The 17 Sustainable Developmental Goals, United Nations Department of Economic and Social Affairs, New York, 2023. Available at: https://sdgs.un.org/goals.

4 J. Wang, H. Kong, J. Zhang, Y. Hao, Z. Shao and F. Ciucci, Carbon-based electrocatalysts for sustainable energy applications. *Progress in Materials Science*, 2021, *116*, 100717. https://doi.org/10.1016/j.pmatsci.2020.100717

5 L. Cozzi, D. Wetzeland and J. Hyppolite, For the First Time in Decades, the Number of People without Access to Electricity Is Set to Increase in 2022, International Energy Agency, Paris, Commentary: 3 November 2022. Available at: https://www.iea.org/commentaries/for-the-first-time-in-decades-the-number-of-people-without-access-to-electricity-is-set-to-increase-in-2022

6 H. K. Jeswani, A. Chilvers and A. Azapagic. Environmental sustainability of biofuels: a review, *Proc. R. Soc. A*, 2020, **476**, 20200351, http://doi.org/10.1098/rspa.2020.0351

7 S. Lomartire, J. C. Marques and A. M. M. Gonçalves. An overview of the alternative use of seaweeds to produce safe and sustainable bio-packaging. *Applied Sciences,* 2022, **12**(6), 3123. https://doi.org/10.3390/app12063123

8 L. I. Budkevich, G. V. Mirzoyan, R. B. Gabitov, M. A. Brazol, P. V. Salistyj, Y. V. Chikinev, A. A. Shmyrin and A. V. Glutkin, Collost bioplastic collagen material for the treatment of burns, *Sovremennye Tehnologii v Medicine,* 2020, **12**(1), 92-96, https://doi.org/ 10.17691/stm2020.12.1.12

9 M. Nasrollahzadeh, M. Sajjadi, S. Iravani and R. S. Varma. Starch, cellulose, pectin, gum, alginate, chitin and chitosan derived (nano)materials for sustainable water treatment: a review, *Carbohydrate Polymers*, 2021, **251**, 116986. https://doi.org/10.1016/j.carbpol.2020.116986

Finalist

How can the chemical science lead the stewardship of the Earth's element resources?

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Over the last few decades, technological advancements have significantly improved various aspects of our lives, including communication, information technology, and consumer products. This progress has resulted in unprecedented levels of comfort, convenience, better medical diagnosis and treatment, more efficient transportation, and access to an immense amount of information that was previously unimaginable. Advances in chemical science have played a crucial role in realizing these technological developments, allowing for the utilization of unique properties of certain elements that were once merely scientific curiosities.

Nonetheless, a considerable portion of this modern technology relies heavily on elements that are in short supply. Elements present in the Earth's crust are crucial for human survival, industrial activities, and economic growth, and are collectively known as Earth's element resources. However, supplies of these elements are now in danger of becoming exhausted, referred to as "endangered elements".[1] It is imperative to sustainably manage their extraction, utilization, reuse, and dispersion, given their critical supply risks. Out of the 118 elements that compose everything, from chemicals used by chemists to consumer products, several elements are now "critical" due to limited supply and environmental concerns surrounding their extraction and use (Table 1). Elements like indium, are usually found as impurities in common ores and their availability is tied to demand for these commodities. Many elements, such as rare earth metals, are critical for various applications but are recycled at low rates. Phosphorus depletion is worrisome as it is essential for food production. While there are enough lithium reserves, its usage should be evaluated based on economic, environmental and supply factors.

Table 1 Critical Elements

Element	Reserves Distribution (%)	Supply Risk	Abundance (ppb)	Uses
Helium	21	6.5	8	MRI technology, fibre optics and arc welding
Indium	Unknown	7.6	52	Electronics, touchscreens, solar panels, transistors and microchips
Neodymium Dysprosium	50	9.5	300	High-performance magnets and lasers
Lithium	58	6.7	16×10^3	Rechargeable batteries
PGM Group Elements Platinum Rhodium Palladium	95	7.6	0.037	Optic fibres, jewellery, dental fillings, pacemakers and catalytic converters.

Source: Ref 8

Chemical sciences play a crucial role in power generation, transportation, electronics and catalysis (Table 2). Designing materials requires consideration of reactivity, functionality, and element availability. The molecular design approach can be used to develop new materials and chemicals that are more sustainable, efficient, and cost-effective and can also help identify ways to use resources more efficiently and reduce waste.[2] Chemical scientists can develop sustainable materials that use fewer critical elements, such as batteries with less lithium and solar panels with less indium. Better batteries are needed for mobile and stationary use, with higher energy power density, stability, safety, and reduced cost. Lithium-ion batteries used in electric cars have limitations and safety issues due to liquid organic electrolytes. Solid, non-combustible electrolytes would improve safety. Second-generation solar devices using thin films are expensive and new materials made of abundant elements are needed for more efficient solar cells. Furthermore, researchers are creating renewable energy technologies like perovskites for solar cells and lithium-sulfur batteries for energy storage. They are also exploring alternative materials like graphene, carbon nanotubes and metal-organic frameworks which have unique properties that could replace or complement traditional materials.[3] Furthermore, research into renewable energy has resulted in an emphasis on magnetic materials in energy devices. Rare earth elements in magnets need to be replaced with cheaper induced magnetic anisotropy in metals and alloys can create efficient and secure magnetic materials. Discovering materials that can superconduct at higher temperatures could solve global energy problems.

Table 2 Sustainable Chemical Science Solutions

Technology	Critical Elements	Application	Sustainable Solutions
Batteries	Lithium Cobalt	Transportation, Electronics	Reduce the use of critical elements like lithium, increase their lifespan, and use recycling and reuse strategies for lithium-ion batteries.
Photovoltaic cells	Indium Silicon	Solar Panels	Create more effective methods of producing silicon suitable for solar panels and develop new materials for solar cells made from more readily available elements.
Magnets	Neodymium Dysprosium	Generators, Wind Turbines	Improve the efficiency of rare earth usage in magnets and eventually replace them with more abundant elements.
Super-conductors	Helium Lanthanides	Medical Imaging, Transportation	Work on developing practical liquid nitrogen-temperature superconductors and increase the efficiency of thermoelectric devices.
Fuel Cell Material	Platinum	Power Generation, Transportation	Develop solid oxide fuel cells that require fewer rare earth elements and create polymer electrolyte fuel cells that use fewer platinum group metals.
Catalyst	Platinum Rhodium Palladium	Catalytic Converters	Enhance catalyst efficacies & reduce contents of critical elements. Strengthen stability of catalysts that experience deactivation quickly. Design self-repairing catalysts that can regenerate and remain effective for an extended period.

Sources: Refs 9, 10

Different types of fuel cells exist, varying in operating temperature, size, and fuel.[4] Lanthanide perovskites are widely used in fuel cells and electrolyzers, but sustainability can be improved by using alternative elements. Low-temperature fuel cells using polymer electrolyte membranes are being developed for mobile applications but face challenges with catalysts and stability. The development of alkaline polymer electrolytes and membranes operable at higher temperatures could offer benefits. Catalysts improve energy efficiency and enable economic processes. New catalysts using commonly available elements, such as metals and metal-free catalysts should be designed. Using widely available elements like iron can be challenging due to their tendency to undergo single-electron reactions, but this could lead to discoveries in organo-catalysis. Discovering new chemistry with these elements can lead to alternative methods without requiring precious metal catalysts, as well as to enhanced selectivity and robustness, especially for base metals, and development of self-healing catalysts to prevent oxidation. Additionally, the chemical sciences are advancing the design of materials for circular economy principles, which aim to keep resources in use for as long as possible, minimize waste and pollution, and regenerate natural systems.[5]

Chemical processes used for mining have major environmental impacts due to toxic chemical release, high energy usage, and water consumption. Chemical scientists are developing eco-friendly and energy-efficient methods, such as bioreactors for extracting metals from low-grade ores and bioleaching for copper extraction. A significant challenge for the chemical sciences is balancing economic growth with environmental protection, as elements required for modern technologies are scarce and their extraction can cause environmental damage. For example, the production of rare earth elements (REEs), which are essential for many high-tech applications, such as smartphones and electric vehicles, is often associated with pollution and social conflicts in countries where they are mined.[6] To mitigate this, innovative approaches are being developed, such as using green solvents and recycling rare earth elements from waste streams.

Chemical scientists are developing new technologies to recover and recycle critical elements from electronic waste, batteries, and other products. Recycling and recovery can reduce the need for new mining operations and ensure that critical elements are available for future generations. Researchers have developed new methods for recovering rare earth elements from electronic waste, which could help to reduce reliance on mining and promote circular economy practices.[7] Recycling of elements like aluminium, iron, and lead is common, and platinum group metals have established recycling protocols due to their high cost. To promote sustainability, new products should consider the entire life cycle and the impact of their elements, critical elements like indium and rare earth elements such as dysprosium used in electromagnets should be recycled and reused, and mining and processing of phosphate should be made more efficient, technology for recovering phosphorus from wastewater should be developed, helium should be captured during natural gas production, helium recycling systems should be developed and actinides should be separated for uranium recycling.

New sustainable technologies and materials developed by scientists rely on societal values and policies. Policymakers can encourage sustainability through regulations and incentives, and society can support sustainable products and policies. The European Union Circular Economy Action Plan is an example of this, which includes measures to increase the circularity of materials and products while minimizing environmental impacts. The United Nations also established the International Resource Panel to advise on the sustainable use of natural resources. To achieve this, collaboration among industry, academia, and national research institutes in a precompetitive manner must be promoted, Large central facilities equipped with sophisticated instrumentation that can host both domestic and foreign researchers must be established, further mechanisms to support and encourage new researchers in these fields must be created and teaching methods to prepare students for these areas should be developed.

In recent decades, technology has advanced rapidly and become an integral part of modern society. However, the demand for certain chemical elements is unsustainable, and there is a need for effective conservation and recovery methods. To address this, chemical science has played a vital role in the stewardship of Earth's element resources. Through the development of new materials, processes and technologies chemical scientists have enabled efficient and sustainable use of resources while minimizing their impact on the environment. One of the key contributions of chemical science is the development of new methods for resource extraction and purification. By using advanced techniques such as molecular engineering and catalysis chemical scientists have been able to extract elements from natural resources efficiently with less environmental impact. Further, the development of methods for the removal of impurities and waste reduction is underway. Additionally, the development of new materials such as carbon fibre and composite material and catalysts enabled the development of fuel-efficient vehicles and renewable energy systems. Moreover, by developing cleaner and more efficient methods for chemical synthesis and manufacturing, chemical scientists would reduce the environmental impacts of industries and improve product quality and efficiency. In conclusion, through the development of new materials, processes and technologies chemical science has ensured that our planet's resources are used responsibly and sustainably, paving the way for a more sustainable future.

REFERENCES

1 J Deakin and Turner, How will we save our endangered elements? Educ. in Chem., 11 February 2019. Available at: https://edu.rsc.org/feature/how-will-we-save-our-endangered-elements/3010098.article

2 M. R. Eden, J. D. Siirola, G. Towler. Proc. 8th Internat.l Conf. on Foundations of Computer-Aided Process Design. Elsevier, London 2014, eBook ISBN: 9780444634429. Available at: https://shop.elsevier.com/books/proceedings-of-the-8th-international-conference-on-foundations-of-computer-aided-process-design/eden/978-0-444-63433-7

3 F. V. Harzand, Farrokhfar, S. N. M. Nejad, A. Babapoor, S. M. Mousavi, et al, Recent advances in metal-organic framework (MOF) asymmetric membranes/composites for biomedical applications, *Symmetry*, 2023, **15**(2), 403. https://doi.org/10.3390/sym15020403

4 H. D. Stryczewska, M. A. Stępień and O. Boiko, Plasma and superconductivity for the sustainable development of energy and the environment. *Energies*, 2022, **15**(11), 4092. https://doi.org/10.3390/en15114092

5 A. P. Velenturf and P. Purnell. Principles for a sustainable circular economy. *Sust. Prod. and Consumption*, 2021, **27**, 1437-1457. https://doi.org/10.1016/j.spc.2021.02.018

6 S. Rangarajan, Shriram, S. P. Sunddararaj, A. V. V Sudhakar, C. K. Shiva, U. Subramaniam, E. R. Collins and T. Senjyu. Lithium-ion batteries – the crux of electric vehicles with opportunities and challenges. *Clean Technol.*, 2022, **4**(4), 908-930. https://doi.org/10.3390/cleantechnol4040056

7 V. Kaim, J. Rintala and C. He. Selective recovery of rare earth elements from e-waste via ionic liquid extraction: a review, *Separ. and Purific. Technol.*, 2022, 306(b), 122699. https://doi.org/10.1016/j.seppur.2022.122699

8 Periodic Table, Royal Society of Chemistry, London, 2023. Available at: https://www.rsc.org/periodic-table/

9 V. Zepf, J. Simmons, A. Reller, M. Ashfield and C. Rennie, Materials critical to the energy industry. An introduction. BP, London, 2nd Edn., 2014.

10 C. J. Rhodes, Endangered elements, critical raw materials and conflict minerals. Sci. Progr., 2019, **102**(4), 304-350. https://doi.org/10.1177/0036850419884

Finalist

Chemical sciences: paving the way for responsible management of the earth's elemental resources

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INTRODUCTION

As the world's population continues to grow, the demand for natural resources increases. However, the Earth's element resources including minerals, metals, and non-renewable fossil fuels, are finite. Therefore, it is vital to promote responsible management of these resources to ensure their availability for future generations. Chemistry, which is the study of matter and the changes it undergoes, is intimately tied to the management of elemental resources. Chemical sciences can help develop innovative and sustainable technologies for the extraction, processing, utilization, and recycling of these resources. Moreover, the chemical sciences can also support policy and regulation related to the stewardship of Earth's element resources. In this essay, we will discuss the importance of scientific approaches grounded in the chemical sciences to manage the Earth's elemental resources, their intersection with society, policy aspects and their contribution to the United Nations' Sustainable Development Goals (SDGs).[1]

RESOURCE EXPLORATION, EXTRACTION AND RECYCLING

Most of the Earth's element resources, such as minerals and fossil fuels, are found in complex geological environments, whose exploration can be challenging and resource-intensive. To identify potential areas for resource exploration, chemical analyses can be helpful. For instance, geochemical surveys can help detect the presence of mineral deposits by analyzing the chemical composition of soils and rocks.[2]

The extraction process of natural resources involves the separation of the desired element or compound from the ore or raw material. Chemical science provides various methods to extract resources. For instance, metals can be extracted by smelting (heating the ore to high temperatures to separate the metal from the other materials) and leaching (using chemicals to dissolve the metal from the ore, and then recovering the metal from the solution).[3] Particularly, some resources require new and more sustainable extraction methods, which are highly dependent on chemical science. For instance, rare earth elements, which are essential components of various high-tech devices including smartphones, computers, and electric cars, are challenging to be extracted due to their extremely low concentrations in ores. One of the most common methods involves crushing the ore into small pieces and then using a combination of gravity separation and magnetic separation to separate the rare earth elements from other minerals. However, this separation is time-consuming and not efficient. Alternatively, the chemical ion exchange method, which involves using a resin that selectively adsorbs the rare earth elements from a solution, was employed.[4] Rare earth elements can also be extracted from coal ash and other waste streams,[5] reducing the need for new extraction from the Earth's crust.

In addition, the most valuable elements are lost in waste streams, such as industrial by-products, electronic waste, and batteries. Recycling and recovering them using chemical science can help conserve the Earth's element resources and reduce the environmental impact of waste disposal. One effective approach is chemical modification, which involves altering the chemical structure of a material to make it more useful or to enable it to be recycled more easily. For example, plastics can be chemically modified to make them more biodegradable or to enable them to be broken down into smaller, more manageable pieces for recycling.[6] Besides, chemical science can pave the road for efficient and effective recycling processes. For example, plastic waste can be converted into monomers or other chemicals through chemical depolymerization, which can then be used to produce new plastic products.[6] In addition, chemical science plays an essential role in increasing energy efficiency during recycling processes. For example, by using chemical catalysts during recycling processes, the energy needed for the recycling process can be significantly reduced.

In this context, chemical science may contribute to achieving Sustainable Development Goal (SDG) 12: responsible consumption and production.

DESIGN OF MATERIALS WITH IMPROVED PROPERTIES

In addition to the methods to manage natural resources, chemical science also plays a key role in developing sustainable materials with increased durability, greater efficiency, and reduced environmental impact. For instance, graphene, a two-dimensional material made of carbon atoms, was developed as a replacement for copper in electronic devices because it is stronger, more conductive, and may reduce the demand for copper. On the other hand, to minimize the environmental impact, new materials that are more easily biodegradable were designed based on chemical science. For instance, biodegradable polymers derived from renewable resources such as starch, cellulose, and proteins were fabricated to replace conventional plastics made from non-renewable resources such as petroleum,[6] and can be used in a variety of applications including packaging, agriculture, and medical implants. In addition, new renewable energy materials (such as dyes, carbon materials, quantum dots, new catalysts, etc.) that are more efficient at storing and converting energy can reduce the reliance on fossil fuels and natural resources.

Chemical science provides several approaches to designing sustainable materials. One approach is to take inspiration from nature (biomimicry). For example, by mimicking the structure and properties of spider silk, artificial fibres were developed, which are strong, lightweight, and biodegradable.[7] Another approach is to develop new materials from renewable resources by using chemical methods. For instance, carbon dots can be developed from plant-based materials, such as cellulose or lignin,[8] which are abundant and renewable. Besides, waste materials can be transformed into new materials with high value. Polystyrene waste can be converted into styrene,[9] which is a valuable building block for the production of other chemicals such as rubber, resins, and plastics.

Thus, chemical science may contribute to achieving SDG 9: industry, innovation, and infrastructure; and to SDG 7: affordable and clean energy.

INTERSECTION WITH SOCIETY AND POLICY ASPECTS

Chemical science intersects with society and policy aspects in many ways including health, environment, energy and education. First, chemicals used in industry and agriculture can influence the environment, including air and water pollution, and contribute to climate change. In this context, chemical scientists can consider the environmental impact of their research and work with policymakers to develop regulations that promote sustainability. Secondly, taking account of the health and safety risks of chemicals, chemical scientists can estimate the potential risks associated with their research and work with policymakers to develop guidelines for the safe use and handling of chemicals. Thirdly, to ensure the chemicals used in consumer products and food additives are safe for public consumption, it is important that consumers, chemical scientists, and policymakers work together to develop a standard that sustainable sources and technologies must fulfill. Finally, chemical science research and innovation should be protected by intellectual property laws. Policymakers can help to balance the interests of the scientific community with those of consumers and industry to ensure that intellectual property laws promote innovation while protecting public health and safety. Thus, chemical science can contribute to SDG 3: good health and well-being.

Overall, chemical science has a significant potential to manage the resources on Earth in various aspects and has a significant potential to promote sustainable development. By developing new technologies and processes, chemical science can help address some of the most pressing challenges facing our planet, such as climate change, pollution, and resource depletion.

REFERENCES

1 S. A. Matlin, G. Mehta, H. Hopf and A. Krief, *Nat. Chem,* 2015, **7**, 941. https://doi.org/10.1038/nchem.2389

2 E. Grunsky and P. de Caritat, *Geochemistry: Exploration, Environment, Analysis,* 2020, **20**, 217-232. https://doi.org/10.1144/geochem2019-031

3 C. R. Borra, B. Blanpain, Y. Pontikes, K. Binnemans, T. Van Gerven,*J. Sust. Metallurgy,* 2017, **3**, 393-404. https://doi.org/10.1007/s40831-016-0103-3

4 E. R. Tompkins and S. W. Mayer, *J. Amer. Chem. Soc.,* 1947, **69**, 2859-2865. https://doi.org/ 10.1021/ja01203a068

5 G. Gaustad, E. Williams and A. Leader, *Resources, Conservation and Recycling,* 2021, **167**, 105213. https://www.sciencedirect.com/science/article/pii/S0921344920305309

6 H. Sashiwa, N. Kawasaki, A. Nakayama, E. Muraki, N. Yamamoto, H. Zhu, H. Nagano, Y. Omura, H. Saimoto and Y. Shigemasa, *Biomacromolecules,* 2002, **3**, 1120. https://doi.org/10.1021/bm0200478

7 A. Rising, J. Johansson, *Nat. Chem. Biol.,* 2015, **11**, 309-315. https://doi.org/10.1038/nchembio.1789

8 M. Kurian and A. Paul, *Carbon Trends,* 2021, 3, 100032. https://doi.org/10.1016/j.cartre.2021.100032

9 Z. Zhang, T. Hirose, S. Nishio, Y. Morioka, N. Azuma, A. Ueno, H. Ohkita and M. Okada, *Ind. Eng. Chem. Res.,* 1995, **34**, 4514 -4519. https://doi.org/10.1021/ie00039a044

Finalist

Chemistry enables greener consumption of rare earth elements

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Earth's element resource is limited. Responsible consumption and production are essential for sustainable management and use of natural resources as envisioned in Sustainable Development Goal 12 (SDG 12). Land management is also critical to combat climate change. The global temperature would continue to rise even if fossil fuels were eliminated overnight, because plants and soils store twice the carbon contained in all known fossil fuel reserves. Ironically, indigenous people are better at managing land. In a 2023 report by the World Resources Institute, only Amazonia regions stewarded by indigenous people are net carbon sinks compared to regions managed by governments and private owners. The root causes are deforestation and mining.[1]

In the 21st century, a mining fever of rare earth elements (REEs) is rampant. REEs include scandium, yttrium and 15 lanthanide elements. The driver of this mining fever is a super-magnet, namely neodymium-iron boron, which has 30 wt% of REEs.[2] It is the largest single use for REEs. It has been used in computer hard drives, electric motors, audio equipment, microwave communication and magnetic resonance imaging (MRI).[3] Its application appears in almost every digital and low-carbon technology[4] such as wind- and solar-energy conversion, optics and lasers, rechargeable batteries, hydrogen storage, supercapacitors and single-molecule magnets[5] (storage and processing digital information especially in quantum computing).

Mining of REEs involves a series of chemical processes. This is where the bad reputation of REE mining and processing originates, as REEs are notoriously difficult to extract and separate from each other. Principal sources of REEs are bastnäsite, monazite and loparite from open pit mining and lateritic ion-adsorption clays from in-situ leaching. Digging of vast open pits degrades the environment. A life cycle assessment of the Bayan Obo mine in China was reported in 2015, which produced 45% of global rare earth oxide (REO). Production of 1 kg heavy REO consumes over 20 times more primary energy as compared to steel.[6] For ion-adsorption mining, life cycle assessment indicates a high concentration of ammonium and sulphate ions, heavy metals mobilisation and eutrophication in freshwater ecosystems.[7] It is inevitable that the mining of REEs is required to meet global demand. Chemists are indispensable to monitor and optimise the method of mining REEs. The life cycle carbon footprint for the operation of each mine should be assessed to eliminate misconduct. Currently, only a handful of studies investigate the environmental impacts of REE production. Only clear and reflective records of environmental impacts can influence the mining policy of local governments and suppliers.

Production of REEs typically starts from ores being converted into high-grade metal concentrates. Oxidative roasting, acid leaching and solvent extraction are followed by refining of concentrates into separated REO.[4] Here, chemists are the inventors and innovators of greener methods in roasting, leaching and precipitation processes which are the primary treatment for REE concentrates. For instance, the efficient removal of thorium and fluorine from ore is a standing issue because thorium is useful in the nuclear industry and fluorine causes environmental degradation. In 2012, Wang and co-workers developed a new process which uses utilises HEH(EHP) (phosphonic acid) extractants to remove $[CeF_x]^{4-x}$ and $[ThF_x]^{4-x}$ from Re(III).[4] This process has been adopted in industry as it prevents pollution of thorium and fluorine. For extracting individual REO, conventional acidic extractants require saponification. More than 10 tonnes of acid and base are usually consumed to separate a tonne of REO, producing a large volume of wastewater. This calls for chemists to innovate this process. In an extraction process adopted in 2010, based on counter-current extraction, chemical consumption for minimum extraction quantity was determined by equilibrium acidity control.[4] Optimum conditions of using HEH(EHP) extractants in HCl system was determined, reducing chemical consumption by nearly 30%.[4] In 2021, a new protein-based process was reported for high-purity separation of REE in a single-column run.[8] This novel approach omits organic solvents but achieves tandem extraction and group separation of REEs from complex feedstock leachate.

Besides sustainability challenges in mining REEs, the ultimate goal of stewardship is not to exploit. A circular economy of REEs should be established, despite record highs of REE quotas in 2021.[9] It is sensible to suggest a threshold for the amount of REEs which can sustain the entire economy. At this point, mining is no longer necessary. When transitioning from the use of one element to another, the afterlife of unused elements should be recycled, repurposed or sequestered back into the Earth. The recycling of plastic is now advocated globally. Why not REEs?

REE waste has two types: end-of-life (EoL) urban waste and industrial waste. Urban waste includes electronic waste, waste catalysts, optical lenses and super magnets. A review from 2023 revealed that total REE recovered versus demand could be standing at 2.23 in 2025. The main REE product/waste in the future economy would be rare earth permanent magnets (REPMs) or super-magnets. Currently, 38% of global REO production is for super-magnet and is expected to reach 68% in 2028.[10] Sources of REPM include *hard disk drives* (*HDDs*), motors, generators and MRI. One REPM typically consists of 15-30% Nd along with 2-5% Dy, Tb and Gd. If efficiently recycled, a significant amount of REEs could be added to the global market. This is even crucial for REEs that are less naturally abundant than the market demands such as dysprosium. 30-year-old magnets comprise 5 wt% or more of Dy, whereas the current Nd(Dy)FeB-magnet only has 1 wt% or less. Recycling could supply plenty of Dy.[2]

Like the chemical processes of extracting REE from ore, recycling builds on chemistry, but it is not entirely similar. REE distribution in tiny electronic parts is small and sometimes dispersed.[3] It is the chemists' role to design, optimise and upscale recycling methods to make recycling magnets cheaper for competing with a low production cost of new magnets.

First, physical separation of REPM from disposed products such as HDDs and MRI has been successfully overcome.[11] Subsequently, the recycling of REPM starts from demagnetisation, crushing, pulverisation, and oxidative roasting, followed by acid leaching, solvent extraction and precipitation. The leaching can be hydrometallurgical and/or pyrometallurgical with choices of different mineral acids (H_2SO_4, HCl, HNO_3). The leached REE is then purified through solvent extraction with choices of commercial extractants before precipitation.[10] However, chemists strive to design greener processes. Biohydrometallurgy was developed in Ames Laboratory to design an acid-free recycling process. It uses bacteria to dissolve and separate REE from shredded electronics.[3] On the other hand, electrolysis using redox-active organic compounds can separate REE quickly by kinetic control on oxidation based on different solubility of REE complexes on different oxidation states.[12]

Besides REE separation technologies, magnet-to-magnet (MtM) recycling is the most active area now. The University of Birmingham has developed a method called hydrogen processing of magnet scrap (HPMS) to liberate NdFeB powders from EoL magnets.[13] This is funded by the REProMag EU-H2020 project. This method uses hydrogen to form metal hydrides which demagnetises the electronics and, separates NdFeB as powder from the rest of the components by milling. The powder is mixed with thermoplastics to form 3D-printing feedstock. Complexly shaped magnets can be produced by injection moulding. The product then undergoes debonding of thermoplastics and sintering to form a new REPM. This chemically-proven recycling process is upscaled in a continued project called SusMagPro.[14] It plans to build 4 recycling and 4 reprocessing plants across Europe, producing a quarter of REPM in Europe by 2027. The circular material flow stream includes magnet extraction, pulverisation and REE extraction, magnet production and new products with improved design for recycling. Successful examples of recycling processes and pilot plants can form the basis for policy and market intervention.

To enable societal changes, efficient waste management and collection are needed. The industry needs chemists to objectively characterise REE-bearing waste. For example, the International Electrotechnical Commission sets the environmental standards for collection and treatment of Waste Electrical and Electronic Equipment. Standards should be established for every REE-bearing waste.[15] Only data such as volume of waste generated, REM content and fate of waste are well-documented, and large-scale recycling plants can be operationalised. The government should promote the use of secondary REEs via regulations which require a minimum amount of recycled REE in products. Manufacturers should be advised to design for recyclability.[15] Chemical knowledge will be essential for the use and distribution of REE in different products. Just like plastics, REE-bearing products should have traceability. New products with NdFeB-magnet can be categorised by technical pre-processing requirements of proven HPMS processes in terms of production method, content and accessibility.[16] Although HPMS is currently the most successful example of recycling NdFeB-magnets, other lab-scale separation processes could be the next budding recycling method. The obstacle is always the lack of attention from the metallurgical industry due to high upfront investment and risks. However, chemists will be pushing forward to design cheaper and greener technologies, especially with the advent of green catalysis.

In essence, recycling is the ultimate solution for the stewardship of the Rare Earth Elements. Basic and applied research is essential to understand the separation chemistry of REE in specific products before any upscaled recycling process can be realised. Before that, the mining of REEs should be as green as possible.

REFERENCES

1 M. Ribel, News Spotlight: Indigenous Land Stewardship Key to Preserving Amazon Carbon Sinks, *Conservation International*, 23 January 2023. Available at: News Spotlight: Indigenous land stewardship key to preserving Amazon carbon sinks (conservation.org)

2 K. Binnemans, P. McGuiness and P.T. Jones, Rare-earth recycling needs market intervention. *Nat. Rev. Materials*, 2021. **6**(6): 459-461. https://doi.org/10.1038/s41578-021-00308-w

3 V. Balaram, Rare earth elements: A review of applications, occurrence, exploration, analysis, recycling, and environmental impact. *Geoscience Frontiers*, 2019. **10**(4): 1285-1303. https://doi.org/10.1016/j.gsf.2018.12.005

4 L. Wang, X. Huang, Y. Yu, L. Zhao, C. Wang, Z. Feng, D. Cui and Z. Long, Towards cleaner production of rare earth elements from bastnaesite in China, *J. Cleaner Prod.*, 2017. **165**, 231-242. https://doi.org/10.1016/j.jclepro.2017.07.107

5 D.N. Woodruff, R. E. P. Winpenny and R. A. Layfield, Lanthanide single-molecule magnets. *Chem.Rev.*, 2013. **113**(7): 5110-5148. https://doi.org/10.1021/cr400018q

6 G. G. Zaimes, B. J. Hubler, S. Wang and V. Khanna, Environmental Life Cycle Perspective on Rare Earth Oxide Production, *ACS Sust. Chem Eng.*, 2015. **3**(2): 237-244. https://doi.org/10.1021/sc500573b

7 R. Schulze, F. Lartigue-Peyrou, J. Ding, L. Schebek, M. Buchert, Developing a life cycle inventory for rare earth oxides from ion-adsorption deposits: key impacts and further research needs. *J. Sust. Metallurgy*, 2017. **3**(4): 753-771. https://doi.org/10.1007/s40831-017-0139-z

8 Z. Dong, J. A. Mattocks, G. J.-P. Deblonde, D. Hu, Y. Jiao, J. A. Cotruvo and D. M. Park, Bridging hydrometallurgy and biochemistry: a protein-based process for recovery and separation of rare earth elements. *ACS Central Science*, 2021. **7**(11): 1798-1808. https://doi.org/10.1021/acscentsci.1c00724

9 T. Daly. China hikes 2021 rare earth quotas by 20% to record highs, *Reuters*, 30 September 2021. Available at: https://www.reuters.com/business/energy/china-hikes-2021-rare-earth-quotas-by-20-record-highs-2021-09-30/

10 B. Swain. Challenges and opportunities for sustainable valorization of rare earth metals from anthropogenic waste. *Revi. Envir. Sci. and Bio/Technol.*, 2023. **22**(1): 133-173. https://doi.org/10.1007/s11157-023-09647-2

11 O. Deubzer et al, Voluntary certification scheme for waste treatment: baseline and gap/obstacle analysis of standards and regulations. 2020, CEWASTE. Available at: https://cordis.europa.eu/project/id/820859/results

12 H. Fang, B. E. Cole, Y. Qiao, J. A. Bogart, T. Cheisson, B. C. Manor, P. J. Carroll and E. J. Schelter, Electro-kinetic separation of rare earth elements using a redox-active ligand. *Angew. Chem. Internat. Edn.,* 2017, **56**(43): 13450-13454. https://doi.org/10.1002/anie.201706894

13 New Rare Earth Magnets from Old. European Commission, Horizon 2020 REProMag Project, https://doi.org/10.3030/636881

14 About SUSMAGPRO - Objectives. SUSMAGPRO 2023; Available at: https://www.susmagpro.eu/about/about-susmagpro-objectives

15 S. Manoochehri et al. A Contribution to future critical raw materials recycling*: CEWASTE Project Final Report*, CEWASTE 2021, ISBN 978-2-9602819-0-3. Available at: https://cewaste.eu/wp-content/uploads/2021/04/CEWASTE-Final-Public-Raport.pdf

16 C. Burkhardt, A. Lehmann, B. Podmiljsak and S. Kobe, A systematic classification and labelling approach to support a circular economy ecosystem for NdFeB-type magnet. *Am. J. Materials Sci. Eng.,* 2020. **10**, 125-133. https://doi.org/10.17265/2161-6221/2020.7-8.001

Finalist

The role of the chemical sciences in the mitigation of resource depletion

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INTRODUCTION

Resource depletion is a problem that has been a focus of administrations and organisations alike across the globe. Now, more than ever, we have become aware of our copious use and disorganised disposal of elemental resources. We have now reached the point where 'the available supply of a range of metals will run out within 50 years or less', according to some researchers.[1] In order to enable a well thought-out response to resource depletion, it is crucial that we manage our element resources effectively. Such responses are often focussed upon the fields of biology and engineering, with the chemical sciences being neglected. However, for us to effectively manage our resources, it is necessary to examine the problem from a chemical standpoint as well.
In this essay, the role of the chemical sciences will be divided into three parts – the first being the extraction of resources, the second being the preservation of resources, and the third being the recycling of resources. While this essay will approach this subject with a broad overview, specific examples will be provided to highlight the various forms that these responses can take.

EXTRACTION OF RESOURCES

The first step of the life cycle of most natural resources is extraction. While fossil fuels are an important consideration, this essay will primarily focus on metallic resources.

Natural resources are distributed relatively unevenly around the world. Momentarily disregarding the political implications of this, this means that the concentrations of these resources will vary across the world. In terms of metals, they will either be found in low-grade ores (which only contain small quantities of the desired metal) or high-grade ores, which contain relatively high concentrations of the desired metal.

Mining has predominantly been done with high-grade ores, as they are the most profitable – for a similar extraction cost, much more metal can be extracted from high-grade ores than low-grade ores. However, with resource depletion, turning to other sources of metals is the next logical step. Although they may not be profitable at present, the dismissal of the use of low-grade ores discourages research into bespoke extraction methods. In order for us to change our resource use, we must not only consider these methods but actively attempt to employ them.

The chemical sciences are often heavily involved in the extraction of metals from high-grade ores, and it is, therefore, reasonable to turn to them for the solution to the extraction of metals from low-grade ores. One example of this is the trademarked Rapid Oxidative Leach method, of FLSmidth.[2] This method involves the use of a stirred media reactor to achieve copper recoveries in excess of 97% from low-grade ores in 6-8 hours.[2] The use of the stirred media reactor has contributed to this in large because unlike methods utilising only one reactor, the chain of reactors has ensured that as much copper as possible is removed from the effluent.[3] This method has overcome some of the difficulties of other types of leaching i.e. time needed. Although there are still some issues with the energy used in the mixing process, the development of such technologies bodes well for the future, as it is only with the thorough exploration of options that we can make them economically viable.

This is one of the main reasons why the chemical sciences are essential in finding solutions to resource depletion, as the prioritisation of efficacy over economic viability will lead to ultimately more sustainable technologies, which do eventually get more affordable.

PRESERVATION OF RESOURCES

The combined effects of the increasing global population and rapid development in Asian and African countries have led to accelerating demand for products, and the non-renewable resources to make them. Most notable are the rare earth metals (REMs) and transition metals i.e. yttrium and neodymium, which are used in electronics.

It is reported[4] that REMs are projected to run out before 2090 with the current consumption growth rate. This will largely be driven by rapid increases in demand in Asia and Africa. However, with static consumption, they will run out by 2856 – a considerably larger time gap. While it is unfeasible to completely reverse resource depletion, delaying it as far as possible is beneficial, to ensure that there is time for more effective sustainable technologies to be employed. The role of the chemical sciences in the preservation of the Earth's element resources should ideally revolve around the idea of finding alternatives. This would not only preserve existing resources but cause minimum hindrance to the development of Asian and African countries.

REMs, notably neodymium, are frequently used in electronics as magnets. However, the chemical sciences have already played a role in exploring alternatives using more abundant metals. In 2022, Lewis developed a patented method to accelerate the production of tetrataenite,[5] an alloy of iron and nickel which was first discovered in iron meteorites. While the natural formation of tetrataenite crystals would take millions of years on Earth, Lewis and her team have worked on a method to arrange the iron and nickel in a structure resembling that of tetrataenite, which exhibits magnetic properties[5] that could make it a feasible replacement to REMs. As this example showed, generating sustainable alternatives to scarce resources, with minimal disturbance to global demand and development, is not only achievable but already in progress. As funding from the U.S. Department of Energy has shown,[5] such solutions are very desirable in tackling this problem.

Other solutions related to the replacement of REMs have been proposed, such as iron-nitride magnets,[6] but the principle of resource alternatives remains a common trait of more successful solutions. Not only does this reduce strain on diminishing resources, but it also reduces the political tension around such resources, as the management and distribution of REMs have been topics of contention between countries. Thus, the chemical sciences have an essential role to play in the preservation of scarce resources, particularly REMs, through the exploration of suitable alternatives.

RECYCLING OF RESOURCES

The last of the three foci of the chemical sciences is the recycling of element resources. Given the rapidly increasing use of metallic resources, their recycling is of the utmost importance. By recycling and re-using these resources, we not only ensure that we have a reliable supply in the future, but also that the prices are not prohibitively high due to shortages.

However, recycling REMs, particularly those from electronics, is difficult for a couple of reasons. Firstly, rates of recycling are low. Most consumers either hoard old electronics or dispose of them in landfills, which decreases the retrieval of these resources. As well as this, the diversity of materials found in smartphones, with some containing up to 65 elements,[7] means that the conventional method of grinding them into a powder and separating them has become time-consuming and expensive, and could even end up harming the environment due to the energy or solvents used.[7]

There are two main solutions to this. The first is the use of widespread public campaigns and industrial subsidies to incentivise the recycling of electronics. However, this would likely take a long time to cause a change, as well as being complicated to enforce. The second, arguably more effective option, is the recycling of industrially used REMs while replacing rare-earth metals in electronics with alternatives (as detailed in the second section of this essay). As large wind turbines can contain multiple kilograms worth of REMs (due to the magnets needed for generators),[7] recycling these would be much more cost-effective, not to mention simpler due to the relative size of the components containing rare-earth metals. As well as this, the phasing out of their use for consumers will ensure decreased usage, without compromising global development.

CONCLUSION

Resource depletion is a difficult problem to tackle. A multi-faceted approach is necessary for any change to be seen in our extraction, preservation and recycling of resources such as REMs. One particularly important point is the gradual phasing in of such measures, rather than an abrupt change. By phasing these methods in gradually, we can ensure that the development of African and Asian countries is not compromised, as consumers can continue to use these resources. By gradually increasing the proportion of products made using these methods, long-lasting change can be enacted, without much resistance from consumers or firms. Ensuring their collaboration through subsidies and public campaigns is also necessary for the success of these methods. However, this essay has proven that the chemical sciences undeniably have a crucial role to play in the mitigation of resource depletion. By increasing funding and support for research in this field, we can ensure that long-term change is enacted, thereby solving the problem.

REFERENCES

1 S. M. Jowitt, G. M. Mudd and J. F. H. Thompson. Future availability of non-renewable metal resources and the influence of environmental, social, and governance conflicts on metal production. *Commun. Earth. Environ.,* 2020, **1**, 13. https://doi.org/10.1038/s43247-020-0011-0

2 *Extracting from low grade ores*. FLSmidth, Copenhagen, 2023. Available at: https://www.flsmidth.com/en-gb/solutions/extracting-from-low-grade-ores

3. M. Mulligan, D. Chaiko, F. Baczek, S. Rocks, C. Eyzaguirre, C. Dickinson and R. Klepper, The FLSmidth® Rapid Oxidative Leach (ROL) process: a mechano-chemical approach and industrial applications for rapid metal sulphide dissolution. J. S. Afr. Inst. Min. Metall., 2017, **117**, 741-747. Available at: https://www.scielo.org.za/scielo.php?pid=S2225-62532017000800005&script=sci_abstract&tlng=en

4 J. Desjardins. A forecast of when we'll run out of each metal, *Visual Capitalist*, 2014. Available at: https://www.visualcapitalist.com/forecast-when-well-run-out-of-each-metal/

5 T. Stening. Accelerating the production of tetratenite as alternative to rare-earth magnets, Northeastern University College of Engineering, 2022. Available at: https://coe.northeastern.edu/news/accelerating-the-production-of-tetratenite-as-alternative-to-rare-earth-magnets/

6 C. Cavallo. What are alternatives to rare earth elements?, *Thomasnet*, 9 February 2023. Available at: https://www.thomasnet.com/insights/what-are-alternatives-to-rare-earth-elements/

7 J. Marshall. *Why rare earth recycling is rare - and what we can do about it*, *Ensia*, 7 April 2014. Available at: https://ensia.com/features/rare-earth-recycling/

Finalist

Hydrogen economy and its role in combining other renewable energy sources for the decarbonization of public sectors

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Since the first discovery of a chemical element (phosphorus in 1669), chemical science has been a problem solver for humankind in many aspects. In today's world, nations around the globe are running toward achieving their common goal of net-zero carbon emissions in 2050 for decarbonizing various public sectors. In that regard, the major issues the global nations are trying to solve are present-day energy scarcity and environmental impacts related to the usage of traditional energy sources. Particularly, the building, industrial, and transportation sectors account for 70% of global greenhouse gas emissions, while relying too much on fossil fuel sources for providing energy to those sectors has created an energy scarcity. Accordingly, this time, chemical science has come to the rescue by letting us know that "switching to renewable energies is the long-term solution for both scarcity and the environmental impacts of fossil fuel sources." Therefore, from the implementation perspective, instead of focusing on one kind of renewable energy source, combining available sustainable energy technologies to match energy supply and demand in the above-mentioned sectors is a promising strategy. Therefore, by acting as a common energy carrier, hydrogen gas (H_2) plays a major role in making a collaborative network of state-of-the-art renewable energy technologies such as wind power plants, solar cells, fuel cells, carbon capture, and water electrolysis. Hence, the process of decarbonizing economic sectors using H_2 as the energy carrier is called the hydrogen economy.[1,2] This essay discusses the possible applications and challenges of the hydrogen economy for decarbonizing various public sectors.[3]

1. GREEN HYDROGEN AS THE ENERGY CARRIER

Sitting at the number one position on the Periodic Table, the chemical element hydrogen is unique in its way of having one proton and one electron without a neutron. In its standard form, hydrogen appears as gas that is presently produced from fossil fuel sources such as natural gas and coal for mainly petroleum refining and ammonia synthesis. This traditional production of H_2 from fossil fuel sources contributes to the emissions of a large volume of greenhouse gases. Further, according to its production methods, H_2 can be classified as 1) black hydrogen, 2) brown hydrogen, 3) grey hydrogen, 4) blue hydrogen, 5) red/pink hydrogen, and 6) green hydrogen. The black hydrogen is produced from the gasification of black coals at higher temperatures (700-800 °C), which majorly results in the emission of CO and CO_2. Then, as the name suggests, brown hydrogen is produced from brown coals. The grey hydrogen is produced from natural gas via steam methane reformation (SMR). It is worthwhile to note that the SMR presently accounts for 95% of global hydrogen production, which releases CO and CO_2 slightly less than the black and brown hydrogen production. Similar to grey hydrogen, blue hydrogen is also produced via SMR of either coal or natural gas, but the released CO and CO_2 are captured and stored underground, resulting in low carbon emissions. Finally, green hydrogen is generated from splitting water molecules (H_2O) into H_2 and O_2.[4] This process is called water electrolysis. Additionally, when nuclear power is utilized to produce hydrogen via water electrolysis, the resultant hydrogen is called pink/red hydrogen. Even though nuclear energy is renewable, the materials used in a nuclear power plant lead to the production of greenhouse gases directly or indirectly. So, the production of green hydrogen is considered zero-carbon emission when the required electricity for the water electrolysis is generated from renewable energy sources such as wind and/or solar power plants. As shown in Figure 1, green hydrogen can act as an energy carrier by combining renewable energy technologies such as wind power plants, solar cells/grids, water electrolysis, carbon capturing, and fuel cells to power the transport sectors, as mentioned before, this network of renewable technologies releases nearly zero greenhouse gases.

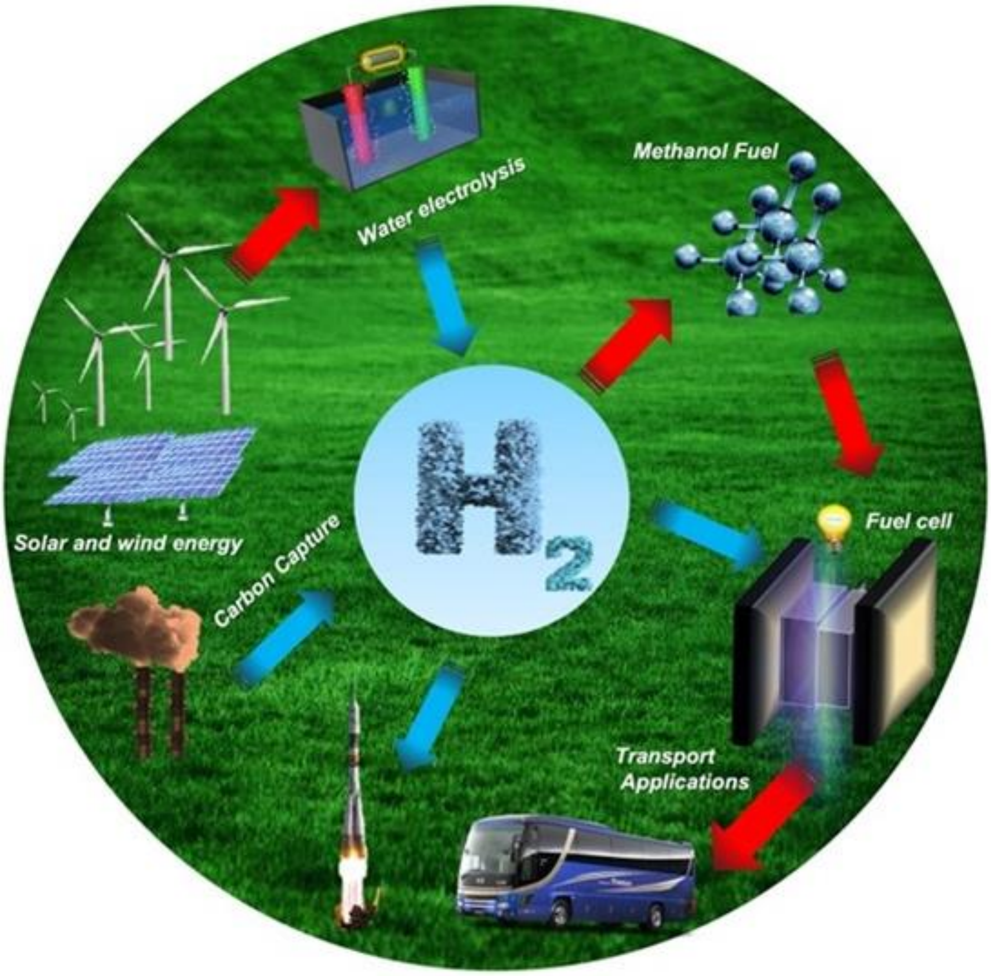

Figure 1 Illustration of how green hydrogen can be used as an energy carrier in the transport sector

2. APPLICATION OF GREEN HYDROGEN IN TRANSPORT AND STATIONARY SECTORS

The proton exchange membrane fuel cell (PEMFC) is an emerging energy conversion device that converts the chemical energy of reactants H_2 and O_2 into electricity with water and heat as only byproducts. So, the operations of water electrolysis and PEMFC are the reverse of one another. However, it should be noted that the theoretical efficiency of H_2 as a fuel is around 85-90%, and using the state-of-the-art components a practical efficiency of 65% can be driven from PEMFC systems. This hydrogen-powered PEMFC is considered a potential replacement for petroleum-powered internal combustion engines in automotive vehicles ranging from cars, buses, trucks, flights, and forklifts. These fuel cell electric vehicles (FCEVs) are considered a keystone in decarbonizing transport sectors, which currently account for 20% of global carbon emissions. On the other hand, the methanol produced from the hydrogenation of CO_2 can be used in PEMFC for stationary applications including charging laptops, mobile phones, and tablets. Meanwhile, switching from hydrogen to methanol in PEMFC leads to low emissions of CO_2. Furthermore, green hydrogen can also be utilized for cryogenic engines of rockets.

3. APPLICATION OF GREEN HYDROGEN IN INDUSTRIAL, BUILDING AND HEALTH SECTORS

In the industrial sector, the production of ammonia, steel and cement is responsible for 13-15% of global carbon emissions. For example, presently, grey or blue hydrogen is being utilized for the production of ammonia, so using green hydrogen for ammonia would be a beneficial strategy for reducing the corresponding carbon emissions. When hydrogen is burned as a fuel, it produces heat and water as the byproducts. So, in the case of steel production, high-temperature furnaces are used by burning mostly fossil fuels, whereas green hydrogen can be used as an alternative. However, in this process, the furnaces and boilers of traditional steel production need to be reconstructed accordingly if hydrogen is used. Similarly, the process of cement production requires heating the kilns to 1450 °C by using coal or other fossil-fuel sources, which can be changed to green hydrogen.

Even though electric heating is recognized as a potential alternative to traditional natural gas for heating buildings, green hydrogen or PEMFC can be used wherever required. Besides, combining electric heating with either green hydrogen or PEMFC is also being considered in the building sectors. Most of the medical equipment used in the health sector necessitates a constant source of energy supply in the form of either electricity or heat. For example, various medical imaging systems such as X-ray, magnetic resonance imaging, radiation detectors, and angiography require an uninterrupted source of electricity.[5] So, implementing hydrogen-powered PEMFC in hospitals, clinics, and biological laboratories is feasible for providing a constant source of electricity and heat.

4. CURRENT CHALLENGES AND FUTURE PERSPECTIVE OF THE HYDROGEN ECONOMY

Although turning to green hydrogen as an energy carrier will result in both economic and environmental benefits,[6] there are major challenges in implementing it for real-time applications. More specifically, the storage method of hydrogen still demands more research efforts for wide commercialization. As hydrogen is a known light element and the release of pure hydrogen in the atmosphere can lead to an explosion, at present, the H_2 gas is stored in high-pressure storage tanks. These storage tanks require sophisticated design and materials, eventually leading to high costs and loss of the H_2 while storing and releasing. In this regard, metal hydrides are seen as the light at the end of the tunnel for storing a high volume of H_2 which is still in the development stage. On the other hand, storing hydrogen in solid form via various chemical derivatives is also in consideration. For instance, green hydrogen can be stored as sodium borohydride ($NaBH_4$). As can be seen in its chemical formula, the $NaBH_4$ molecule holds four hydrogen atoms which can be mobilised by reacting with water (in the presence of a catalyst) as shown in equation (1).

$$NaBH_4 + 2H_2O \rightarrow NaBO_2 + 4H_2 \qquad (1)$$

In addition to $NaBH_4$, metal hydrides, ammonia borane and dimethyl ammonia borane are also studied for solid hydrogen storage. Apart from storage, there are other issues related to components of the hydrogen economy that are being discussed by researchers. Particularly, the cost of PEMFC components and their durability need to be improved. Since battery-powered electric vehicles (BEVs) are being commercialized as light-duty vehicles such as cars and bikes, the possible application of PEMFC technology in those domains is being questioned. However, for medium and heavy-duty applications including buses and tracks, PEMFCs are still proven to be more efficient than batteries. Also, it is a fact that the refuelling time of FCEVs is faster than the recharging time of BEVs. In some cases, the possibility of combining batteries for storing and PEMFCs for generating electricity for designing a hybrid EV is being examined. Furthermore, the construction of sophisticated components for carbon capture, hydrogenation, hydrogen furnaces, and boilers is so far not cost-effective. Nevertheless, we have to understand that no scientific revolution takes place overnight. The implementation of a scientific solution to a public problem not only results in solving the problem but also opens of variety of new opportunities such as employment, economic growth, and environmental friendliness.

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REFERENCES

1 P. M. Falcone, M. Hiete and A. Sapio, Hydrogen economy and sustainable development goals: review and policy Insights. *Curr. Opinion Green Sust. Chem.*, 2021, **31**, 100506. https://doi.org/10.1016/j.cogsc.2021.100506

2 A. M. Oliveira, R. R. Beswick and Y. Yan. A green hydrogen economy for a renewable energy society, *Curr. Opinion Chem. Engin.*, 2021, **33**, 100701, https://doi.org/10.1016/j.coche.2021.100701

3 M. Yue, H. Lambert, E. Pahon, R. Roche, S. Jemei and D. Hissel, Hydrogen energy systems: a critical review of technologies, applications, trends and challenges. *Renewable Sust. Energy Revs.s*, 2021, **146**, 111180. https://doi.org/10.1016/j.rser.2021.111180

4 E. B. Agyekum, C. Nutakor, A. M. Agwa and S. Kamel, A critical review of renewable hydrogen production methods: factors affecting their scale-up and its role in future energy generation. *Membranes*, 2022, **12**(2), 173, https://doi.org/10.3390/membranes12020173

5 E. Aydinli and H. Göksu. Use in the healthcare industry of the hydrogen energy produced by solid hydrogen sources used in fuel cells, *Sağlık Bilimlerinde Değer*, 2022, 171–174, https://doi.org/10.33631/sabd.1055536

6 S. van Renssen, The hydrogen solution? *Nat. Clim. Change*, 2020, **10**(9), 799–801, https://doi.org/10.1038/s41558-020-0891-0

Finalist

The chemical journey for clean and sustainable energy

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Energy is a very common process in our daily routine. We have heard this term used in physics class and it is described as "the ability to do work." Energy comes in many forms, such as heat energy, sound energy, chemical energy, nuclear energy, electrical energy, and more. However, energy cannot be limited to physical processes, as it plays a role in our society in many ways. In modern society, all activities require energy to function, and they can make a difference in the quality of life. For this reason, since 2015, the United Nations has been working to *"ensure access to affordable, reliable, sustainable and modern energy for all"*.[1]

According to the International Energy Agency (IEA), 774 million people worldwide lack access to electricity for the most common activities such as lighting, food refrigeration, cooking, efficient transportation, or cooling in hot temperatures.[2] Ensuring electricity can reduce poverty, increase economic growth, and improve living standards. On the other hand, energy production, transportation, and use of oil or coal can have negative impacts on people's health.

As the world's population grows, so does the demand for energy, and renewable energy sources are the answer to providing abundant, affordable, safe, and clean energy. Renewable energy comes from solar, wind, hydro, biofuels and other sources. Because renewable energy is replenished faster than it is consumed, it plays an important role in reducing carbon dioxide emissions, and helping to mitigate climate change, consistent with the Paris Climate Agreement.[3] Within renewable energy sources, solar photovoltaic (PV) and wind power make a larger contribution to electricity generation. In 2021, solar power accounted for 3.6% of global electricity generation (shown in Figure 1).[4] However, the path to decarbonization presents some challenges and requires modernization of the way electricity is generated, and this is where PV systems play an important role.

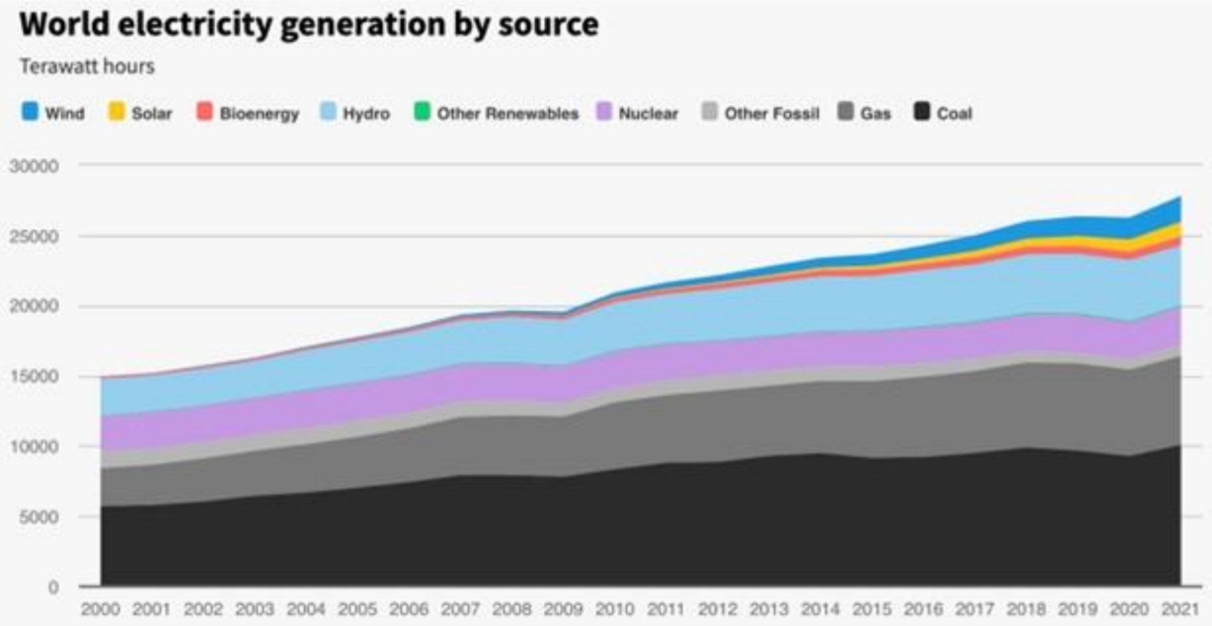

Figure 1 World electricity generation by source reported in 2021 (Source: Ember[8] CC BY-SA 4.0)

Promoting research in PV systems is crucial because solar energy has become one of the cheapest forms of energy on the planet and can produce clean and sustainable energy.[5] PV devices work based on the photoelectric effect and convert sunlight into electricity using solar cells made of semiconductor materials. A single solar cell can generate 1 to 2 watts of power. Several of these solar cells are connected together and encapsulated with plastic or glass to form a photovoltaic module that can also be used outdoors.

Solar cells, like other renewable technologies, are still in research and focus on providing sustainable and real technologies. This means that PV devices are designed to exhibit high average conversion efficiency using semiconductors with high affinity to the environment.[6-7] At the present time, three generations of solar cells have been proposed. The differences in chemical composition make it possible to obtain PV systems with different characteristics, but all with the same goal, which is to increase the average conversion efficiency.

The first generation is well known, as crystalline and polycrystalline Si-based modules dominate the current market. Although Si is an abundant element in the Earth's crust, the average conversion efficiency (about 21-25%) is still one of the parameters to be improved.[9] The second generation corresponds to thin film technologies, in which cadmium telluride (CdTe) and copper indium (gallium) diselenide (CIGS and CIS) are the commercially used semiconductor materials. This technology offers the possibility of obtaining flexible devices compared to the first generation since a lower amount of semiconductor material is needed to fabricate each cell. However, the main disadvantage is the use of toxic and scarce elements with lower average conversion efficiency than Si cells.[10] Finally, the third generation includes organic photovoltaics (OPV), dye-sensitized solar cells (DSSC), and perovskite solar cells (PSC). In the case of OPV, these devices use dyes or organic semiconductors as absorber layer material. Despite the possibility of producing flexible and semi-transparent modules at low production costs, commercial organic solar cells are not yet available on the market, but are considered a promising photovoltaic technology for the future.[11]

As mentioned earlier, all PV generations have different properties to offer to the current market, but there is still much to be done to provide efficient energy conversion devices, and in this quest, scientists are pushing the use of innovative semiconductor materials with the required properties for solar components. In general, solar cells are constructed sandwich-like with a photoactive layer and an electron/hole transport material between a positive and negative electrode, and electron/hole transport materials. The photoactive layer is the most important component because the absorption of light, diffusion and recombination of excitons, and charge carrier diffusion take place here.[12]

Generally, semiconductors used in the photoactive layer exhibit adequate band gap (in the range of 1.1 eV to 1.7 eV) and high thermal and chemical stability.[13] In the search for alternatives, Earth-abundant materials and conducting polymers have attracted considerable interest as photoactive layers. Currently, promising alternatives include quaternary p-Cu_2ZnSnS_4 (CZTS), FeS_2 (pyrite), and conducting polymers such as polythiophene and its derivatives.

FeS_2 (pyrite) is an Earth-abundant, nontoxic, and low-cost semiconductor. It is potentially considered a promising photovoltaic material due to its outstanding electronic and optical properties, such as a direct band gap at 1.05-1.10 eV comparable to Si (1.1 eV), a high absorption coefficient ($\alpha > 10^5$ cm^{-1}, two orders of magnitude larger than the absorption coefficient of Si), and a theoretical efficiency of about 31%.[10] Moreover, FeS_2 is a particularly suitable material for large-scale use at low cost, since it is possible to fabricate photovoltaic systems with thin absorber layers (< 20 nm). However, solar cells with pyrite exhibit low open-circuit voltages (V_{OC}) and the energy conversion efficiency is below 3%.[14-15]

Similar to FeS_2, CZTS is a semiconductor composed of elements abundant in the Earth's crust and is also a promising candidate for thin film solar cells due to its suitable band gap (1.5 eV), large optical absorption coefficient ($\alpha = 10^4$ cm^{-1}), and theoretical efficiency of about 32.1%. However, the highest energy conversion efficiency is about 11%. The main reasons limiting the overall performance are the strong non-radiative recombination, the presence of crystal structure defects and the difficulty in obtaining a single- phase since a mixture of stannite and kesterite phases is likely to form during synthesis.[16-17]

On the other hand, organic semiconductors also have some promising approaches such as conducting polymers. Conducting polymers have been synthesized by a variety of methods and exhibit properties such as tunable electrical conductivity (from 10^3 to 10^4 $S \cdot cm^{-1}$), ease of fabrication, lightweight, easy processability, and capability to fabricate flexible electronic devices. However, for polymer solar cells, conversion efficiency (about 10%), spectral range, chemical stability and device stability need to be improved for large-scale applications.[18,19]

As stated, the performance of the device depends on the physical and chemical properties of the semiconductor, and these emerging solar cells need further improvement to enhance their photovoltaic performance for large-scale applications that can meet clean energy needs.

Scientists around the world are advancing research into innovative and highly efficient technologies that can ensure universal access to clean and sustainable energy. However, this remarkable progress is limited until the gender gap is narrowed, as the number of female researchers worldwide[20] is about 30%, while in the photovoltaic industry (the largest renewable energy employer), only 40% of full-time positions are held by women.[21] The inclusion of women in STEM careers and in renewable energy sectors such as solar PV must be part of the main goal: to ensure access to affordable, reliable, sustainable, and modern energy for all. Adequate representation will allow women to use their talent to improve the actual performance of solar cells, to develop and design new environmentally friendly semiconductor materials with excellent optoelectronic properties, and also to be leaders in the use of PV devices.

In perspective, various efforts are being made to develop new energy solutions that ensure access to clean and sustainable energy. As more nations, cities, and people realize the environmental, social, and economic benefits of clean energy and promote the use of alternative energy such as PV solar, everyone will have a chance at a bright and sustainable future.

REFERENCES

1 Energy. Department of Economic and Social Affairs United Nations, New York, 2023. Available at: https://sdgs.un.org/topics/energy,

2 World Energy Outlook 2022, International Energy Agency, Paris, 2022. Available at: https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf

3 The Paris Agreement. What is the Paris Agreement?, United Nations, New York, 2023. Available at: https://unfccc.int/process-and-meetings/the-paris-agreement

4 Solar PV Analysis. International Energy Agency, Paris, 2023. Available at: https://www.iea.org/reports/solar-pv

5 Renewables were the world's cheapest source of energy in 2020, new report shows. World Economic Forum, 5 July 2021. Available at: https://www.weforum.org/agenda/2021/07/renewables-cheapest-energy-source/

6 M. B. de la Mora, O. Amelines-Sarria, B. M. Monroy, C. D. Hernández-Pérez and J. E. Lugo, Materials for downconversion in solar cells: Perspectives and challenges, *Sol. Energy Mater. Sol. Cells,* 2017, **165**, 59-71. https://doi.org/10.1016/j.solmat.2017.02.016

7 E. Płaczek-Popko, Top PV market solar cells 2016, *Opto-Electronics Rev.,* 2017, **25**, 55-64. https://doi.org/10.1016/j.opelre.2017.03.002

8 Global electricity review 2022. Ember, London 2022. Available at: https://ember-climate.org/insights/research/global-electricity-review-2022/

9 L. C. Andreani, A. Bozzola, P. Kowalczewski, M. Liscidini and L. Redorici, Silicon solar cells: toward the efficiency limits, *Adv. Phys.: X*, 2019, **4**(1), 1548305. https://doi.org/10.1080/23746149.2018.1548305

10 V. Muteri, M. Cellura, D. Curto, V. Franzitta, S. Longo, M. Mistretta and M. L. Parisi, Review on life cycle assessment of solar photovoltaic panels *Energies*, 2020, **13**(1), 252. https://doi.org/10.3390/en13010252

11 W. Hou, Y. Xiao, G. Hanand J. Y. Lin. The applications of polymers in solar cells: a review, *Polymers*, 2019, **11**(1), 143. https://doi.org/10.3390/polym11010143

12 C. Zhao, J. Wang, J. Jiao, L. Huang and J. Tang, Recent advances of polymer acceptors for high-performance organic solar cells, *J. Mater. Chem. C.*, 2020,**8**,28–43. https://doi.org/10.1039/C9TC05567C

13 N. Asim, K. Sopian, S. Ahmadi, K. Saeedfar, M. A. Alghoul, O. Saadatian, et al., A review on the role of materials science in solar cells, *Renew. Sustain. Energy Rev.*, 2012, **16**, 5834-5847. https://doi.org/10.1016/j.rser.2012.06.004

14 R. Sai and R. A. Abumousa, Impact of iron pyrite nanoparticles sizes in photovoltaic performance, *Coatings*, 2023, **13**(1), 167. https://doi.org/10.3390/coatings13010167

15 M. Z. Rahman and T. Edvinsson, What is limiting pyrite solar cell performance? *Joule*, 2019, 3, 2290–3. https://doi.org/10.1016/j.joule.2019.06.015

16 S. Kim, J. A. Márquez, T. Unold and A. Walsh, Upper limit to the photovoltaic efficiency of imperfect crystals from first principles, *Energy Environ. Sci.,* 2020, 13, 1481-91, https://doi.org/10.1039/D0EE00291G

17 C. Yan, J. Huang, K. Sun, S. Johnston, Y. Zhang, H. Sun, et al., Cu_2ZnSnS_4 solar cells with over 10% power conversion efficiency enabled by heterojunction heat treatment *Nat Energy*, 2018, **3**, 764–72. https://doi.org/10.1038/s41560-018-0206-0

18 K. Namsheer and C. S. Rout, Conducting polymers: a comprehensive review on recent advances in synthesis, properties and applications *RSC Adv.*, 2021, **11**, 5659–5697. https://doi.org/10.1039/D0RA07800J

19 Q. Fan, Q. An, Y. Lin, Y. Xia, Q. Li, M. Zhang, et al, Over 14% efficiency all-polymer solar cells enabled by a low bandgap polymer acceptor with low energy loss and efficient charge separation, *Energy Environ. Sci.,* 2020, **13**, 5017-5027. https://doi.org/10.1039/D0EE01828G

20 Women in Science. UNESCO Institute for Statistics, Paris, Fact Sheet 55, June 2019., Available at: https://uis.unesco.org/sites/default/files/documents/fs55-women-in-science-2019-en.pdf

21 Solar PV: a gender perspective, International Renewable Energy Agency, Abu Dhabi, September 2022, ISBN: 978-92-9260-466-0. Available at: https://www.irena.org/publications/2022/Sep/Solar-PV-Gender-Perspective

Finalist

How can the chemical sciences lead the stewardship of the Earth's element resources?

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The chemical sciences have a unique and important role to play in the stewardship of the Earth's element resources. As the discipline that is primarily concerned with the study of matter and its transformations, chemistry provides critical insights into the properties and behaviours of elements, compounds, and materials. This knowledge can be leveraged to develop new and innovative approaches to managing and conserving Earth's element resources in a sustainable and responsible manner.

DEVELOPMENT OF NEW MATERIALS AND PROCESSES THAT ARE MORE EFFICIENT, LESS RESOURCE-INTENSIVE, AND LESS ENVIRONMENTALLY HARMFUL THAN CURRENT PRACTICES

This includes the use of green chemistry principles to reduce the use of hazardous materials and promote the use of renewable resources. For example, the development of biodegradable plastics and polymers that can be produced from renewable resources can help reduce the dependence on non-renewable resources and minimize the environmental impact of waste disposal.[1]

A number of research studies have demonstrated the potential of green chemistry principles in reducing the environmental impact of the chemical industry. One study explored the use of renewable resources in chemical synthesis, showing that it can result in significant reductions in energy consumption, waste production, and greenhouse gas emissions.[2] Similarly, another study introduced the concept of the 12 principles of green chemistry, providing guidelines for the design of chemical processes that are more sustainable and environmentally friendly.[1,3]

Another important role that the chemical sciences can play is in the development of new technologies and methods for the extraction and processing of element resources. This includes the development of more efficient and environmentally friendly mining techniques, as well as the development of technologies for the recovery of elements from waste streams and other unconventional sources.[4] For example, research is currently underway to develop new techniques for the recovery of rare earth metals from electronic waste, which could help reduce the need for mining of these scarce resources.[4] One of the key challenges in the mining industry is the generation of large amounts of waste materials, which can cause environmental damage if not managed properly. To address this challenge, researchers are developing new approaches for the management of mine waste, such as the use of bioremediation to remove contaminants from mining wastewater.[4] A study demonstrated the effectiveness of using a bioreactor to treat wastewater from a mining operation, showing that it can remove up to 95% of the pollutants present in the water.[3,4]

CONDUCTING RESEARCH AND ANALYSIS THAT HELPS US BETTER UNDERSTAND THE ENVIRONMENTAL AND SOCIETAL IMPACTS OF OUR CONSUMPTION PATTERNS[3]

This includes the development of life cycle assessments (LCAs) and other tools for evaluating the sustainability of different products and processes, as well as the development of methods for monitoring the environmental impacts of mining and other resource extraction activities. LCA is a widely used tool for evaluating the environmental impact of products and processes. LCAs can help identify the stages of a product's life cycle that have the greatest environmental impact and suggest strategies for reducing this impact. For example, a study used LCA to compare the environmental impact of two different polymers, one produced from fossil fuels and one produced from renewable resources.[1,2,3] The study found that the renewable polymer had a lower environmental impact than the fossil fuel polymer, highlighting the potential benefits of using renewable resources in the production of materials. In addition to LCAs, researchers are also using analytical tools and methods to monitor the environmental impacts of mining and other resource extraction activities.[4] For example, a study used high-resolution satellite imagery to map the impacts of mining on forest cover in Ghana, showing that mining activity had a significant impact on forest loss and fragmentation. The chemical sciences can play a critical role in the stewardship of the Earth's element resources by developing new materials and processes, advancing mining and extraction technologies, and conducting research and analysis to better understand the environmental and social impacts of our consumption patterns. Below are some examples of how the chemical sciences are leading in these areas.

DEVELOPING NEW MATERIALS AND PROCESSES

Chemistry provides a wealth of knowledge on the properties and behaviours of elements, compounds, and materials. This knowledge can be leveraged to develop new and innovative approaches to managing and conserving Earth's element resources in a sustainable and responsible manner. For example, research is being conducted to develop new materials for energy storage, such as sodium-ion batteries, that use abundant and low-cost elements instead of rare and expensive ones.[5] Another example is the development of biodegradable plastics and polymers that can be produced from renewable resources, reducing the dependence on non-renewable resources and minimizing the environmental impact of waste disposal.

ADVANCING MINING AND EXTRACTION TECHNOLOGIES

The chemical sciences can contribute to the development of new technologies and methods for the extraction and processing of element resources. For example, researchers are developing more efficient and environmentally friendly mining techniques that use less water, energy, and chemicals. Additionally, advances in hydrometallurgical techniques, such as leaching and solvent extraction, can help recover metals from low-grade ores or electronic waste, reducing the need for the mining of scarce resources.

CONDUCTING RESEARCH AND ANALYSIS

The chemical sciences can also contribute to the stewardship of Earth's element resources by conducting research and analysis that helps us better understand the environmental and societal impacts of our consumption patterns. For example, life cycle assessments can be used to evaluate the environmental impacts of different products and processes throughout their entire life cycle, from raw material extraction to disposal. Additionally, researchers can use analytical tools and methods to monitor the environmental impacts of mining and other resource extraction activities, helping to identify and mitigate environmental risks.

EDUCATION AND OUTREACH

The chemical sciences can play a role in educating the public and policymakers about the importance of sustainable use of Earth's element resources. This includes raising awareness about the environmental and social impacts of our consumption patterns and advocating for more sustainable policies and practices.

RECYCLING AND REUSE

The chemical sciences can help develop new and innovative ways to recycle and reuse elements and materials. This can help reduce our reliance on virgin resources and minimize waste and pollution.

SUSTAINABLE EXTRACTION

The chemical sciences can contribute to the development of more sustainable methods for extracting elements from the Earth. This includes reducing the environmental impact of mining and refining processes and finding ways to extract elements from unconventional sources such as waste streams or seawater.

LIFE CYCLE ANALYSIS

The chemical sciences can help evaluate the environmental impact of products and processes throughout their life cycle. This includes assessing the impact of raw material extraction, production, use, and disposal.

GREEN CHEMISTRY

The chemical sciences can promote the development of green chemistry principles that prioritize the use of non-toxic, renewable, and biodegradable materials. This can help reduce the environmental impact of chemical processes and products.

INNOVATION AND RESEARCH

The chemical sciences can continue to drive innovation and research in areas such as energy storage, renewable energy, and sustainable materials. These advances can help reduce our reliance on non-renewable resources and mitigate the environmental impact of human activities.

In summary, the chemical sciences can contribute to the stewardship of the Earth's element resources in numerous ways. From sustainable extraction and recycling to green chemistry principles, by developing new materials, advancing energy efficiency and promoting education and awareness. Through research, innovation, and collaboration, scientists and engineers can help build a more sustainable future for all.

REFERENCES

1 R. A. Sheldon. Metrics of green chemistry and sustainability: past, present, and future. *ACS Sustain. Chem. Eng.* 2018, **6**, 32-48. https://doi.org/10.1021/acssuschemeng.7b03505

2 T. G. Ambaye, M. Vaccari, F. D. Castro, S. Prasad and S. Rtimi. Emerging technologies for the recovery of rare earth elements (REEs) from the end-of-life electronic wastes: a review on progress, challenges, and perspectives. *Environ. Sci. Pollut. Res. Int.* 2020, **27**, 36052-36074. https://doi.org/10.1007/s11356-020-09630-2

3 A. Santos, A. Barbosa-Póvoa and A. Carvalho. Life Cycle Assessment in Chemical Industry- a Review. *Curr. Opin. Chem. Eng.* 2019, **26**, 139-147. https://doi.org/10.1016/j.coche.2019.09.009

4 T. E. Graedel, R. Barr, C. Chandler, T. Chase, J. Choi, L. Christoffersen, E. Friedlander, C. Henly, C. Jun, N. T. Nassar, D. Schechner, S. Warren, M.-Y. Yang and C. Zhu. Methodology of metal criticality determination. *Environ. Sci. Technol.* 2012, **46**, 1063-1070. https://doi.org/10.1021/es203534z

5 J.-Y. Hwang, S.-T. Myung and Y.-K. Sun. Sodium-ion batteries: present and future. *Chem. Soc. Rev.* 2017, **46**, 3529-3614. https://doi.org/10.1039/C6CS00776G

Finalist

Chemical sciences steward Earth

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INTRODUCTION

The stewardship of Earth's element resources is crucial for the sustainable development of human societies. The chemical sciences play a crucial role in this endeavour, as they are responsible for the production, use, and disposal of many of the materials that make up modern society. In this essay, we will explore how the chemical sciences can lead the stewardship of Earth's element resources.

BACKGROUND

The Earth's element resources are essential for human development and progress. They are used in various industries, such as construction, transportation, energy, and electronics. However, the extraction, production, and consumption of these resources have adverse impacts on the environment, including air and water pollution, land degradation, and climate change. Furthermore, the supply of some elements, such as rare earth elements, is limited, and their production is concentrated in a few countries, leading to geopolitical tensions and conflicts.

The chemical sciences have a crucial role to play in addressing these challenges. The chemical industry is one of the largest users of element resources, and hence it can contribute to their sustainable use by developing more efficient and environmentally friendly production processes. Furthermore, chemists can design new materials that require fewer resources or are recyclable, reducing the demand for virgin materials. Finally, chemists can develop technologies for the recovery and recycling of elements from waste streams, reducing the dependence on primary resources.

EFFICIENT PRODUCTION PROCESSES

The chemical industry is responsible for the production of various materials, such as metals, plastics, and fertilizers, among others. These processes often require large amounts of energy and generate significant amounts of waste and emissions, contributing to climate change and other environmental problems. Hence, developing more efficient and sustainable production processes is crucial.

Chemists can contribute to this effort by developing new catalysts and reaction conditions that require less energy and generate fewer emissions. For example, researchers have developed new catalysts for the production of ammonia, a critical component of fertilizers, that require less energy and emit less carbon dioxide. Similarly, new technologies, such as microwave heating and continuous flow reactors, can reduce the energy consumption and waste generation of chemical processes.

Furthermore, the development of renewable energy sources, such as solar and wind power, can reduce the dependence of the chemical industry on fossil fuels, reducing the environmental impact of chemical production. Furthermore, the use of renewable feedstocks, such as biomass, can reduce the dependence on fossil resources.

DESIGN OF SUSTAINABLE MATERIALS

The design of sustainable materials is another area where the chemical sciences can contribute to the stewardship of Earth's element resources. Many materials used in industry, such as plastics and composites, are not easily recyclable, leading to their accumulation in landfills and oceans. Furthermore, some materials require rare or toxic elements, leading to the depletion of these resources and environmental risks.

Chemists can contribute to this effort by designing new materials that are recyclable, biodegradable, or require fewer resources. For example, researchers have developed new polymers that can be easily recycled or biodegraded. Similarly, researchers have designed new materials that can replace rare elements, such as gallium, in electronics. Furthermore, researchers have developed new methods for the production of materials, such as graphene, that require fewer resources and generate less waste.

In addition to designing sustainable materials, chemists can also contribute to the development of new technologies for the recycling of materials. For example, researchers have developed new methods for the recycling of plastics, such as chemical recycling, that can convert plastic waste into valuable feedstocks for chemical production.

RECOVERY AND RECYCLING OF ELEMENTS

Finally, the recovery and recycling of elements from waste streams is another area where the chemical sciences can contribute to the stewardship of Earth's element resources. Many materials used in industry, such as metals and rare earth elements, are not easily renewable and can lead to environmental problems if not managed properly. By developing new technologies for the recovery and recycling of these elements, chemists can reduce the demand for primary resources and minimize the environmental impact of their extraction and production.

For example, researchers have developed new methods for the recovery of metals from electronic waste, such as leaching and solvent extraction. Similarly, researchers have developed new technologies for the recycling of rare earth elements from magnets and batteries. Furthermore, researchers have developed new methods for the extraction of metals from mining waste, such as bioleaching and phytomining, which can reduce the environmental impact of mining.

CONCLUSION

The chemical sciences have a crucial role to play in the stewardship of Earth's element resources. By developing more efficient and sustainable production processes, designing sustainable materials, and developing technologies for the recovery and recycling of elements, chemists can contribute to the sustainable use of these resources and the protection of the environment. The challenges of resource scarcity, environmental degradation, and climate change require a concerted effort from all sectors of society, and the chemical sciences have a unique and important role to play in this endeavour.

Finalist

The fate of e-waste within circular economy

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Since the first electronic devices were produced, the environment has faced yet another source of consumption and pollution. Raw materials for their manufacturing include metals, non-metallic materials, rare earth elements, and petroleum, each of which has an impact related to their extraction, processing and ultimately, their disposal. The investigation of how the electronic industry has impacted the environment throughout the production cycle is a matter of deep and long examination because it is not only related to the materials used. It is also related to the evolution of manufacturing technologies, the device's lifetime and moreover, the fate of unused devices.

It has been estimated by The Global E-Waste Monitor 2020 published by the United Nations that each year more than 54 million metric tons of electronic waste, or e-waste, are produced globally. If the observed trend is maintained, the world is set to generate up to 74 million metric tonnes annually by 2030.[1] In general, the growth of this type of waste has been promoted by three main factors: shorter lifespans, higher consumption rates and few repair options. Within the ambitious circular economy paradigm, where all products should find their way into a continuous stream of production, consumption and disposal, this situation threatens to become unsustainable. The depletion of non-renewable materials for their manufacture and e-waste ending up in landfills goes against every principle established by a circular economy system. At first glance, this may seem a problem to be solved by policymakers and manufacturers, so how could the chemical sciences contribute?

To produce electronic devices, the constituent metals, non-metals, ceramics, rare earths, and plastics are required in different amounts. Among these raw materials, precious metals play an important role as their overall economic value is significant. Gold, platinum, silver, nickel, tin and copper are found in small percentages in printed circuit boards (PCBs). For instance, PCBs in computers, mobiles, and tablets contain around 20% copper, 0.2% silver, 0.04% gold, 0.01% palladium, 0.7% tin and 1.1% nickel.[2,3] As of 2020, precious metals found in e-waste accounted for at least US$ 14 billion annually and only the equivalent of US$ 4 billion was recovered.[1,2] The economic loss is only a minor side of the issue, with the major aspect being the environmental and health damages.

Although policies are being designed to resolve the issue, they are still far from successful due to the reigning inequality between high- and low-income countries. Up to 2019, Europe had the highest recycling rate, 42%, while Africa had the lowest at 0.9%.[1] It has been reported that e-waste export is a common practice, where collected devices are sent to countries with deficient labour laws that expose workers to unsafe practices such as the open-air burning of PCBs for copper collection or exposure to toxic heavy metals.[2–4] Leaving aside the ethical implications of such practices, e-waste is destined to either fill up the already overflowing landfills or to be recycled in appropriate settings.

When e-waste finds its way into landfills, electronic components lay bare in a harsh environment, where atmospheric conditions and mechanical damage promote their breakdown. Toxic compounds such as lead or mercury can then leach into soil and water, poisoning potential agricultural and cattle fields, as well as sweet water sources for farming activities and human consumption. Further, not only toxic metals can be damaging but also plastics. For instance, evidence has been found to support the presence of microplastics in human breast milk with unknown long-term effects.[5]

In the exceptional case, when e-waste has been collected for recycling, it still faces difficulties. Sorting and recycling processes are still inefficient. To recover valuable components, e-waste first must be disassembled manually to separate metal-containing components from others that can be hazardous or simply non-metallic. In the case of metal-containing components, these are ground or pulverized so that the metal fraction can be collected through differences in specific gravities, as well as by electrostatic or magnetic separations.[2,3] Once this step has been completed, metals are recovered through two techniques: smelting and leaching.

Smelting is a pyrolytic process for the recovery of metals, particularly copper, in which ground PCBs are incinerated and further processed through electrorefining to produce copper cathodes. Precious metals can then be recovered through digestion where pre-treated e-waste is exposed to a leaching environment in alkaline or acid reactors. Metals are subsequently purified through solvent extraction, electrolytic, or adsorption techniques.[2–4] What occurs with the remaining materials (i.e., ceramics and plastics) is harder to define as the mixture of components limits their separation and purification.

Within the chemical sciences, research on e-waste recycling has been mainly focused on the development of metal recovery processes that are more environmentally- and operator-friendly, and that recover metals with higher purity and rates. The trend is to move away from pyrometallurgical methods and closer to hydrometallurgical or even bio-based processes. Conventional pyrolytic techniques involve high energy consumption (e.g., some processes require heating stages of up to 1200 °C for 12 h), and they release of toxic compounds (e.g., dioxins).[4] These disadvantages are overcome by hydrolytic techniques, which are more efficient, and energy effective. However, the use of high volumes of flammable solvents and acidic or caustic solutions creates a problem for their disposal.

Bio-based metallurgic processes are therefore the more benign, as they are fully green technologies. They consist of the recovery of metals by microbial agents, completely performed in aqueous environments, at ambient temperature and pressure, with high selectivity by choosing the appropriate microorganism, and with reduced greenhouse gas emissions. Still, these biological treatments require long incubation times, high diluted volumes (i.e., low pulp densities) and the presence of some base and heavy metals can interfere with the process.[2,4]

Although the panorama could appear to be desolate, chemical sciences could also impact the very first stages of e-waste recycling. Until now, the initial disassembly of electronic devices has been performed manually and, to a lesser extent, through robotic platforms. For instance, Apple has developed robots capable of disassembling and sorting iPhones and their components. Yet, it is easy to see why this approach is far from being widespread, as it would require adaptation for each brand and model of electronic equipment, from televisions to smartwatches.

A chemical approach to this issue could be related to the development of reversible adhesives that would ease the disassembly process. Reversible adhesives are those adhesives whose detachment is triggered by their exposure to a specific stimulus. This can be a change in temperature, the application of an electric field, exposure to radiation or a magnetic field, or even a change in pH.[6] Research on this area is just starting to become of interest worldwide and most of the existing formulations have yet to find their way into industrial production and commercialization. The holy grail of such technology would be an adhesive made from renewable resources, which could be easily applied, with thermal, electrical, and mechanical properties that meet the requirements, and that could be reversed under benign conditions.

The issues surrounding the fate of e-waste involve actions from a variety of fronts. First, policies that hold companies accountable for the e-waste they generate. Second, strategies that ensure all geographical zones have access to collection systems and that consumers are aware of them. Third, proper regulations for the treatment processes to minimise the environmental impact and operational hazards. Fourth, the development of technologies that facilitate repairs, upgrades, and the overall recycling process. It is this final point where scientists and engineers can contribute, by investigating and developing greener processes and materials that could find a place beyond journal publications.

The clock is ticking and e-waste generation is steadily growing. We must address this challenge from every possible perspective: manufacturers, policymakers, government, and consumers. From our trenches, chemical scientists can lead the way to find strategies to decrease the exploitation of non-renewable resources and to make recovery processes safer and more efficient. It is only with the right technology that e-waste integration into a circular economic system can succeed.

REFERENCES

1 V. Forti, C. P. Baldé, R. Kuehr and G. Bel, The Global E-waste Monitor 2020: Quantities, flows and the circular economy potential, United Nations University/United Nations Institute for Training and Research, International Telecommunication Union, and International Solid Waste Association, 2020, ISBN Digital: 978-92-808-9114-0. Available at: https://ewastemonitor.info/wp-content/uploads/2020/11/GEM_2020_def_july1_low.pdf

2 E. Hsu, K. Barmak, A. C. West and A.-H. A. Park, Advancements in the treatment and processing of electronic waste with sustainability: a review of metal extraction and recovery technologies, *Green Chem.*, 2019, 21, 919–936. https://doi.org/10.1039/C8GC03688H

3 M. Kaya, *Waste Manag.*, Recovery of metals and nonmetals from electronic waste by physical and chemical recycling processes. waste management, 2016, 57, 64–90. https://doi.org/10.1016/j.wasman.2016.08.004

4 D. Dutta, R. Rautela, L. K. S. Gujjala, D. Kundu, P. Sharma, M. Tembhare and S. Kumar, A review on recovery processes of metals from e-waste: A green perspective, *Sci. Total Environ.*, 2023, 859, 160391. https://doi.org/10.1016/j.scitotenv.2022.160391

5 A. Ragusa, V. Notarstefano, A. Svelato, A. Belloni, G. Gioacchini, C. Blondeel, E. Zucchelli, C. De Luca, S. D’Avino, A. Gulotta, O. Carnevali and E. Giorgini, Raman microspectroscopy detection and characterisation of microplastics in human breastmilk, *polymers*, 2022, 14, 2700. https://doi.org/10.3390/polym14132700

6 A. Sierra-Romero, K. Novakovic and M. Geoghegan, adhesive interfaces toward a zero-waste industry, *Langmuir*, 2022, 38, 15476–15493. https://doi.org/10.1021/acs.langmuir.2c02436

Finalist

A sustainable future for chemical sciences and the Earth

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With the imminent threat of climate change looming over us, an even harsher light has been shed on the unsustainable way we are currently living. With concepts such as Earth Overshoot Day (this is the date every year when humanity's demand for resources and emissions, mainly CO_2, exceeds what the planet can regenerate in that same year)[1] giving people a clearer idea of our impact, the pressure is on to find alternative ways to live. While many chemical scientists are passionate about moving towards a more sustainable future, it can't be ignored that the chemical field is a big contributor to some of these issues.

Scientists are already driving an effort towards reducing the use of toxic starting materials used to make products that aren't degradable and contribute to a large part of our waste pollution problem.

Unfortunately, a large part of the problem is replacing methods, products and systems that are already installed and in use worldwide. Years of research have been poured into all areas of science to yield revolutionary breakthroughs, only to discover the negative environmental impacts of them and have to return to the drawing board to begin altering to help move towards greener methods. The improvements needed to combat pressing issues such as climate change, all start with research. It's this research that can lead to the innovation needed to replace the outdated systems we currently use.

Nine planetary boundaries were set out to define the safe operating spaces in which humanity can continue to develop, but without crossing the threshold of potentially irreversible damage to the planet. Recent information has revealed that many leading chemicals are going beyond the limits of these planetary boundaries, pushing for change to be made not only in research but also in industry. The involvement of all sections of chemistry will allow more stewardship to be taken, and a force for chemistry to become more sustainable.[2] It is especially important for industrial chemistry to start making this move as it is the profiting companies that will be able to start distributing the greener alternatives to some of the traditional methods we have now. There are numerous ways this can be achieved, but the introduction of circularity is extremely important. This will consider the starting materials, production, usage, and then end of life – whether that's (ideally) recycling or correct disposal. In regard to starting materials, the use of non-toxic and biobased materials is critical, but equally so is aiming towards materials that are abundant and conserving the element resources that remain.

Currently, a lot of research only focuses on improving certain aspects of a product's lifecycle, meaning a lot of the sustainable alternatives we have cannot actually be deemed a green replacement. A good example of this is lithium-ion batteries used as an energy source and in various other systems which have previously relied on non-renewable fossil fuels that emit greenhouse gases that are rapidly progressing global warming to the life-threatening limits of the 1.5 °C model. This substitution is used very often, especially with widespread plans to reduce usage of heavy metals and can be integrated into the systems with relative ease. However, the replacement being relatively easy does not necessarily make it the most sustainable. This and all other current efforts are a drastic improvement, desperately trying to minimise the threat of global poverty and the extreme effects on ecosystems, but still require far greater effort to get them to work more efficiently and economically than the currently implemented methods. While the use of a lithium battery itself doesn't emit any CO_2, the manufacturing of an 80-kWh battery would produce anywhere from 3-16 tonnes of the abundant greenhouse gas.[3] Not only does this production cause issues, but the extraction of the lithium metal demands around 500,000 gallons of water per metric tonne of lithium,[4] which not only is an intensive strain on the world's water supply but also causes ethical concerns for places such as Chile where lithium mining occurs, as it can leave locals with little to no water, affecting food production. This violates one of the UN's 17 Sustainable Development Goals, as clean water and sanitation[5] are being violated for the locals of the mining areas. Finally, the end of life of these batteries causes issues. The batteries contain metals such as cobalt and nickel, which can contaminate water supplies, and also cause fires in landfills. These batteries must be disposed of properly, preferably by recycling them to introduce circularity into their life cycles, especially due to lithium being a finite resource that could potentially be depleted.[6] This highlights an issue with a lot of renewable resources relying on non-renewable resources to make them, a good example being silicone used for making solar panels.

It is crucial to recognise that, whilst the end of life of a product is an important concern for not only the scientific community but also the greater population, there should be an equal emphasis on the start. Starting materials of products should aim to be bio-based, non-toxic, abundant and cheap.

Laws and protection must be taken so that resources aren't exploited to the point of overconsumption. More of an effort should be made to push for recycling and better disposal of already extracted elements.

Cheap materials for these alternatives are a big factor in moving forward with the transition to a more sustainable future. Large companies, especially those in the fuel market, profit from easy and cost-effective business, even if it is detrimental to the environment. There are other methods of generating electricity, but none have been implemented as the main source of this energy. This can be due to more everyday factors such as the efficiency of the method, the national grids still being fossil fuel-based, insufficient energy storage, or a government's lack of commitment to investing in greener alternatives. While a lot of the focus is on scientists to produce these better alternatives, there is the responsibility of companies and governments to make these available for everyone to use. Unfortunately, greener alternatives aren't as profitable for these larger companies, so there is less interest in switching. So, while chemical sciences should continue their advances in these fields, more of an effort should be made to help support this research and implement it.

International organisations such as the UN have already laid out different goals and agreements to attempt to slow climate change and prevent us from rising above the current 1.1 °C above pre-industrial level. The 17 Sustainable Development Goals span a range of different issues, from gender equality to responsible consumption and production. These aim not only to keep the Earth habitable but to also make it liveable for everybody on it. The goals that are more focused on the environment and quality of life, which inevitably go hand in hand, are all ways that countries can aim towards avoiding the 1.5 °C warming limit set out by scientists. The limit, or target, is the main aim of the Paris Agreement. These agreements and goals have been implemented to reduce greenhouse gases and reach net zero by 2050 and are a great example of how countries and government bodies should be coming together to prevent a global catastrophe. Unfortunately, the current rate of emissions means that the commitments aren't sufficient to satisfy the agreement,[7] so changes still need to be made, whether that's by making new protective laws, or limiting the greenhouse gases we produce.

To conclude, people with scientific backgrounds should be given more of a say in what happens to the consumption of precious minerals and metals that are being extracted quicker than they're being regenerated. An added sense of responsibility would aid in how these resources are used. If more of a focus could be placed on recycling the resources we have already used and introducing circularity into more aspects of science, then less time and energy would have to be devoted to mining and depleting our resources.

All areas of STEM must work together to achieve this, by combining expertise and methods to achieve the progress that we desperately need to see.

REFERENCES

1 Earth Overshoot Day . Available at: https://www.overshootday.org/about-earth-overshoot-day/

2 S. A. Matlin, S. E. Cornell, A. Krief, H. Hopf, G. Mehta. Chemistry must respond to the crisis of transgression of planetary boundaries, *Chem. Sci.*, 2022,13, 11710-11720 . https://doi.org/10.1039/D2SC03603G

3 I. Crawford. How much CO_2 is emitted by manufacturing batteries? MITMECHE: Environmental Solutions Initiative, 1 March 2022. Available at: https://meche.mit.edu/news-media/how-much-co2-emitted-manufacturing-batteries

4 S. Bauer, Explainer: the opportunities and challenges of the lithium industry. Diálogo Chino, 2 December 2020. Available at: https://dialogochino.net/en/extractive-industries/38662-explainer-the-opportunities-and-challenges-of-the-lithium-industry/

5 The 17 goals. United Nations, New York, 2023. Available at: https://sdgs.un.org/goals

6 P. Pyakurel, Lithium is finite – but clean technology relies on such non-renewable resources. The Conversation, 11 January 2019. Available at: https://theconversation.com/lithium-is-finite-but-clean-technology-relies-on-such-non-renewable-resources-109630

7 UN Sustainable Development Goals – Goal 13: Climate action, United Nations, New York, 2015. Available at: https://www.un.org/sustainabledevelopment/climate-change/