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Engagement of early-career scientists in sustainable chemistry: science policy perspectives

Lovish Raheja,[a] Francisca J. Benítez,†*[bc] José Ferraz-Caetano,[d] Maulline G. Leviev,[e] Aanchal Saxena[f] and Anna Isabel Becker[g]

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As global sustainability challenges become more complex and interconnected, the engagement of scientists, and specifically early-career chemists in policymaking, is gaining urgency. This perspective highlights the current status of science policy engagement in chemistry across all continents. It identifies key institutional models, regional disparities and opportunities for action. Using examples from Europe, the Americas, Africa, Asia and Oceania, we explore how chemists are engaging and shaping the science policy interface. We argue that coordinated frameworks, youth-driven initiatives and regionally grounded strategies are essential for advancing sustainable chemistry on a global scale.

Sustainability spotlight

We showcase how early-career chemists around the world are contributing to science policy engagement in response to pressing sustainability challenges. From resource governance in Africa to institutional support in Europe, we explore regional approaches and urge the development of coordinated, inclusive frameworks that empower early-career chemists to advance sustainable chemistry globally.

Introduction

Contemporary global development has triggered a new set of sustainability crises, manifesting in pervasive pollution, acceleration of climate change and critical loss of biodiversity (also referred to as 'the triple planetary crisis'), among others.[1] These challenges are mobilising urgent and transformative scientific actions, rendering the investigation of underlying structures and the design of mitigation strategies an area of increasing focus for both academia and industry.[2,3]

Current literature reveals that industrial development and its cascading impacts, along with the continued interlinked processes of climate change, biodiversity loss and pollution, have been associated with the ongoing triple planetary crisis.[4–6] Within this context, the chemicals sector has played a significant role in worsening the crisis by contributing substantially to the total greenhouse gas and other toxic emissions.[7–14] Hence, addressing the crisis requires a transformation of the chemical sector. This would necessitate a comprehensive strategy that inculcates the idea of 'design, manufacture and the use of environmentally benign chemical products and processes that prevent pollution, reduce or eliminate the use and generation of hazardous waste, and reduce risk to human health and the environment'. This strategic approach is guided by the principles of what is known as 'sustainable chemistry'.[15,16]

Early-career chemists, equipped with novel perspectives, interdisciplinary acumen and a long-term vision, hold a unique position in driving this paradigm shift towards sustainable chemistry.[17] Their inherent motivation for systemic change underscores the critical need to embed sustainable principles, (for example, green chemistry and circular economy) early within education and professional trajectories.[18]

Given the urgency of these challenges and the unique opportunities they present, this perspective article aims to uncover pathways spanning academia, industry innovation and policy engagement. These pathways would enable early-career chemists to actively advance sustainable chemistry, spanning academia, industry innovation, and policy engagement. We also conduct an overview of the status of such advancements in various geographical contexts, by identifying challenges and developing a holistic framework for early-career chemists' engagement in sustainable chemistry from a science policy

[a]IITB-Monash Research Academy, Mumbai, India
[b]Laboratoire de Chimie Théorique (LCT), Sorbonne Université CNRS, Paris, France
[c]Donostia International Physics Center (DIPC), Polymers and Advanced Materials Department, Faculty of Chemistry, University of the Basque Country UPV/EHU, Paseo Manuel de Lardizábal 3, Donostia-San Sebastián, 20018 Spain
[d]LAQV-REQUIMTE, Department of Chemistry and Biochemistry, Faculty of Sciences, University of Porto, Rua do Campo Alegre, S/N, 4169-007 Porto, Portugal
[e]George Mason University, Arlington, VA, USA
[f]Institute of Public Policy, National Law School of India University (NLSIU), Bangalore, India
[g]International Sustainable Chemistry Collaborative Centre (ISC3), Germany
† Current affiliation: Donostia International Physics Center (DIPC); Polymers and Advanced Materials Department, Faculty of Chemistry, University of the Basque Country UPV/EHU, Paseo Manuel de Lardizábal 3, Donostia-San Sebastián, 20018, Spain, francisca.benitez@dipc.org

perspective. Before we dive into the core ideas of this perspective article, we present a brief background of sustainable chemistry to contextualise the subsequent discussion. The following sections will shed light on the engagement pathways for early-career chemists and the policy environments that enable their engagement.

Sustainable chemistry and green chemistry: origins and early development

Efforts to prevent industrial pollution started in the 1970s and 1980s. These efforts were prompted by the escalating environmental pollution from chemical waste, effluent discharges and atmospheric emissions, together with mounting health impacts and major industrial accidents.[19] Waste reduction and the elimination of hazardous substances to human health and the environment emerged as focal responses in the late 1980s and early 1990s.[20] This sub-section follows the recent historical outline made regarding chemistry policy development.[19]

The Rio Declaration within Agenda 21 in 1992 called for intensified research into the development of safe substitutes for chemicals with long life cycles.[21] At a public policy level, the United States Environmental Protection Agency (US EPA) introduced the term 'green chemistry' to promote it in the early 1990s. In 1996, the European Commission (EC) Directive (96/61/

Lovish Raheja

Lovish Raheja is a research scholar at IITB-Monash Research Academy, working in the area of Circular Economy in the Context of Food Supply Chains. Previously, he completed his Masters in Environmental Studies and Resource Management from TERI School of Advanced Studies. He leads the science for policy team and serves on the executive board at the International Younger Chemists Network (IYCN), IUPAC. He is also a task force member of Project CHEMRAWN and Project SysTSCI at the IUPAC and serves as a Coordination Member at the Chemicals and Waste Youth Platform and Research Lead at the Enact Earth Foundation.

Francisca J. Benítez

Francisca J. Benitez is a Chilean chemistry teacher with a background in experimental and theoretical/computational chemistry. She holds an MSc from the Universidad de Concepción and a PhD from the Pontificia Universidad Católica de Chile. With a strong interest in science communication and science-policy engagement, she has been involved in international initiatives such as #LatinXChem and the International Younger Chemists Network (IYCN). Following a research appointment at Sorbonne Université, she is currently a postdoctoral researcher at the Donostia International Physics Center (DIPC), where her research focuses on eutectozyme-based biomaterials design.

José Ferraz-Caetano

José is a Portuguese chemist, historian and philosopher of science. He is a MIT Portugal PhD Program Alumni with the LAQV-REQUIMTE (Faculty of Sciences, University of Porto, Portugal), specializing in AI for chemical property prediction and inverse molecular design. He received two visiting appointments at the MIT (USA) and the NAIST Data-Driven Chemistry Lab (Japan). He was also a Fulbright Scholar with the University of California, Irvine (USA), working on the dynamics of scientific knowledge on emerging science-based legislation. José is also a member of the International Younger Chemists Network – Science Policy Team (Website: https://www.jfcaetano.com/).

Maulline G. Leviev

Maulline Leviev is a scientist, legal strategist, and policy advisor bridging science and society. She holds a PhD in Optics and Quantum Chemistry from Siberian Federal University and studied particle physics at Oxford and sustainability at Reichmann Institute. With degrees in theoretical physics and mathematics, she translates high-level science into governance, law, and justice. She advises governments across the Middle East, Sub-Saharan Africa, and Eastern Europe on science-driven policy, youth participation, and legal frameworks for emerging technologies. Her work, including chairing an EU renewable energy team in Africa, leverages AI, quantum chemistry, and optics to empower youth and women in STEM.

EC)[22] came into force and required integrated pollution prevention in chemical and other types of industrial production.

In 1998, the 12 principles of green chemistry were published, 'summarising what was already focused in industry'.[23] Related to pollution prevention efforts, these remarks can be recapped as safely synthesising less hazardous chemicals, reducing energy consumption and generating less waste. While there are clear merits of the aforementioned efforts, products synthesised accordingly are not necessarily greener or more sustainable, since they do not consider the basic principles of sustainability.[23]

In the 2000s (Fig. 1),[24] the circular economy was 're-invented, after the basic concept had already been elaborated upon in 1982'.[25,26] Here, a zero-waste industry was envisioned,[27] which, although ideal, was precluded by the laws of thermodynamics.[28] In practice, today's pattern of resource use and product waste reflect an economic logic that assumes unlimited material availability, often ignoring the physical constraints of nature.[29] While the popular narrative surrounding the circular economy often draws inspiration from natural cycles, it frequently overlooks their limitations. This is particularly true in the case of energy inputs and material losses that make the perfect circularity impossible. This disconnect reveals a need to move beyond simplistic analogies and engage with deeper structural questions about how economic and industrial systems operate within ecological boundaries.[30]

In contrast to the often technocratic or overly optimistic visions of a circular economy, sustainable chemistry offers a more grounded and holistic framework by focusing on the desired function of a substance or material. Therefore, alternative ways of fulfilling the intended function without using chemicals (non-material-based delivery of service and function) are considered first. 'Chemical service' ranks second, as it

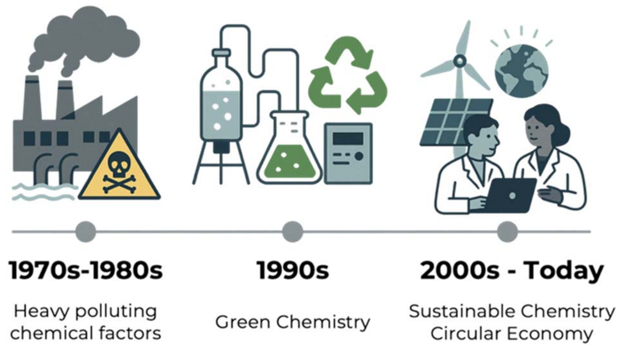

Fig. 1 Graphical depiction of the emergence of the concept of sustainable chemistry (1970s–Present).

represents an important perspective and approach for making chemical use more sustainable. Sustainable chemistry addresses the shortcomings of green and circular chemistry. It seeks to embed the chemical sector within sustainability (currently framed by the Sustainable Development Goals (SDGs)) and the planetary boundaries by identifying the contributions of sustainable chemistry to sustainable development. This encompasses all three strong sustainability strategies: sufficiency, consistency and efficiency, and is based on an ethical background. This process engages all stakeholders along the life cycle of products.[31] Fig. 1 presents a graphical summary of the concepts discussed previously.

Within this scope, through a systems-thinking lens, chemical innovation is viewed as embedded in socio-ecological and techno-economic systems.[32] This refers to mapping stocks and flows throughout the entire value chain, identifying leverage points at which design or policy changes can yield sustainability gains.[33] These assessments can include environmental factors, social measures and governance.[34] Methods such as influence

Aanchal Saxena

Aanchal Saxena is an interdisciplinary researcher and aspiring public policy professional currently pursuing her Master's in Public Policy at the National Law School of India University, Bengaluru. With a background in Chemistry from the University of Mumbai, she aspires to bridge the worlds of science, governance, and social justice through research.

Anna Isabel Becker

Anna Isabel Becker is the Policy Director at the International Sustainable Chemistry Collaborative Centre (ISC3), where she leads global policy advocacy and fosters science-policy dialogue on sustainable chemistry. With a strong background in government relations, public policy, and stakeholder engagement, she bridges innovation, regulation, and education. Her academic journey includes studies at the University of Passau, University of Vienna, University of Melbourne, and Universidade do Minho. She is currently advancing her expertise at UC Louvain. Passionate about sustainability and youth engagement, Anna contributes to international forums and initiatives driving the Sustainable Development Goals through responsible innovation.

diagrams, scenario analysis, multi-criteria decision analysis and innovation protocols enable chemists to compare alternatives under uncertainty within planetary boundaries.[35] In practical terms, it means beginning from 'service and function' to evaluating chemical and non-chemical options over a single process metric. To equip early-career chemists with the systems perspective required for these challenges, education and training should encompass a defined set of competencies: (i) life-cycle and systems mapping from feedstock to fate;[36] (ii) risk–benefit appraisal under uncertainty, including tradeoff and burden-shifting analysis;[37] (iii) data and digital literacy;[38] (iv) policy and economic fluency;[39] and (v) ethics and justice in chemical decision-making.[40]

Through its holistic approach and 'systems thinking', sustainable chemistry considers important interfaces, especially in the extraction and the use of natural resources, waste management or climate protection. It focuses not only on a substance's environmental compatibility, but also on the opportunities and risks of its use, production and disposal.[31]

From a public policy point of view, efforts have increased in the past years. In the European Union (EU), the European Commission's Chemicals Strategy for Sustainability, which was adopted in 2020 as part of the European Green Deal, coupled the goal of 'a toxic-free environment with safe-and-sustainable-by-design chemicals'.[41] In the United States, the White House Office of Science and Technology Policy (OSTP) through the National Science and Technology Council's Sustainable Chemistry Strategy Team, has articulated a complementary federal vision in its 2023 Sustainable Chemistry Report. It then framed the Federal Landscape, proposing a definition and attributes of sustainable chemistry.[42] Such legislative appropriation helps to further densify the complexity of public policies. Nevertheless, it is worth noting that green chemistry, circular chemistry and sustainable chemistry are neither synonymous, nor mutually opposed. Green chemistry and circular chemistry both are important tools for greener and more circular products from chemical industries and the entire chemical sector. However, the decisive point is whether sustainable chemistry, using systems, service and function-oriented thinking, is allowing chemistry to contribute to sustainable development in a sustainable manner.[43,44]

Sustainable chemistry: emerging potential using analytical tools, and implementation challenges

A benchmark of green chemistry applications has been Life-Cycle Assessment (LCA) research as a decision support tool, particularly within the energy and chemical industries. It enables companies to quantitatively assess the environmental impacts of a product or process throughout its entire life cycle, from raw material extraction to manufacturing, use and disposal.[45,46] In the context of chemical Research and Development (R&D), LCA helps identify stages at which energy use, emissions, or waste generation can be minimised. A key related concept that aligns with LCA is atom economy, which is a measure of how efficiently raw materials are converted into final products with minimal by-products or waste.[47,48] When used together, LCA and atom economy provide complementary insights: LCA offers a broad, system-level view, while atom economy targets molecular-level efficiency. Together, they guide the design of greener processes and support progress towards the SDGs through evidence-based assessments.[47,48]

Despite having emerged as a strategic response to increasing regulatory and political pressure, green chemistry implementation faces significant barriers.[49] Fragmented regulations, minimal scale-up funding and weak institutional incentives have been creating a gap between academic progress and policy uptake.[50] In fact, the related laws of many countries focus on exposure control rather than hazard elimination, offering little support for safer alternatives.[51] This stagnation, which is attributable to its core to a lack of effective cooperative action, demonstrates the need for chemists to be involved in policy making. Their unique position has allowed them to understand both the molecular basis of sustainability and the systemic impact of regulation, helping bridge science and policy.[52]

Chemists across academic and industrial settings, along with students pursuing chemistry or related curricula, must develop sustainability awareness. This expertise will be critical for addressing global policy challenges.[53] Nonetheless, a significant barrier remains among science students and with respect to their intention to contribute to sustainability.[54,55] Often, students do not have the interdisciplinary tools to judge the wider environmental and socio-economic impacts of the decisions they make in chemistry. Collaborative networks have the potential to counter this, when strengthened by equitable global partnerships that provide opportunities for real-world problem-solving.[56] For example, digital-native chemists can build crucial bridges to sustainability by leveraging state-of-the-art computational tools.[57] Their familiarity with technology places them in a strong position to engage with digital chemistry. This insight can complement green chemistry, by enabling the timely identification of sustainable solutions, optimisation of reaction conditions and reduction of resource-intensive experimentation.

In co-creation with scientists, future green chemistry policy frameworks should leverage transformative digital collaboration to maximise policy effectiveness. Data-informed and adaptive guidelines provide a pathway for shifting policy focus from chemical control to hazard elimination. These frameworks now allow policy development to move in tandem with scientific advancement, opening new possibilities for sustainable chemistry regulations.

Advancing sustainable chemistry: pathways for early-career chemists within and beyond academia

Avenues in academic environment

Centring sustainability in research and education. Early-career chemists can play a pivotal role in the advancement sustainable chemistry by prioritising research that is focused on green chemistry principles, including the development of non-toxic synthetic methodologies and the exploration of renewable and bio-based materials.[58] Integrating green chemistry metrics, such as atom economy and LCA into chemistry curricula and laboratory practices is vital for cultivating a deep understanding of the environmental and economic impacts of chemical processes.[59] Furthermore, fostering interdisciplinary collaborations at the intersection of chemistry, environmental science and data science can catalyse innovative solutions to complex sustainability challenges.[60]

Student and university-level engagement. Within academic institutions, early-career chemists can spearhead the creation of sustainability-focused student groups, and organise impactful events such as seminars, workshops, and conferences for broader dissemination of the principles of sustainable chemistry.[61]

Actively participating in university-level initiatives can foster lasting engagement with sustainable chemistry throughout diverse academic circles. Organising inter-university conferences, engaging in science policy internships, facilitating interdisciplinary dialogues and leading solution-focused workshops may help translate scientific knowledge into impactful policy recommendations.

Community outreach initiatives alongside the development of educational programmes and curricula for schools can help broaden, integrate and reinforce the understanding and the scope of sustainable chemistry among non-specialists.[62]

Beyond academia: practical engagement pathways

Science communication and public advocacy. Early-career chemists, through their participation in diverse community networks, enable broader outreach by connecting scientific expertise with social, educational and policy-facing audiences. Through communication platforms such as blogs, social media and podcasts, they can translate complex sustainable chemistry concepts for policymakers and the public, advocating for evidence-based policy decisions.[63]

This public engagement is strengthened through citizen science initiatives and community outreach programmes, which build public literacy in environmental monitoring and chemical safety; this creates informed constituencies that support science-based chemical regulations.[64] For example, participating in policy briefings, writing op-eds for policy publications or presenting at legislative hearings translates research into actionable policy insights.

Industry and innovation. Entrepreneurship and intrapreneurship enable early-career chemists to demonstrate the viability of sustainable chemistry in practice. By developing sustainable materials such as bio-based polymers as plastic alternatives, collaborating with industry partners to adopt greener technologies and documenting economic feasibility, they can provide concrete evidence that informs policy frameworks for chemical regulation and fair transition to sustainable practices.[65,66] Engaging in regulatory consultations or serving on industry-government advisory boards ensures that early-career perspectives inform chemical safety standards and green chemistry incentives.

Science policy and governance engagement opportunities

While public policy and governance have historically sought science primarily for technical expertise, we argue that early-career chemists have the potential to change this dynamic. Through their increasing exposure to evolving political landscapes and interdisciplinary perspectives, they can help bridge scientific knowledge and policy needs, positioning science as an integral component of governance decisions.

Several organisations and platforms play an enabling role in facilitating early-career chemists' engagement with sustainability-oriented science policy processes. To illustrate how such engagement is supported in practice, this perspective highlights selected examples. The selection was based on the following criteria: (1) explicit early-career engagement pathways with demonstrated policy influence; (2) geographic diversity spanning global, regional and national scales; and (3) structured programmes, training initiatives or networks offering clear entry points that address the challenges identified in the following sections and highlighted in Table 1 (section: Bridging regional challenges and enablers). Together, these examples illustrate replicable engagement models accessible across diverse contexts.

Several platforms provide structured pathways for early-career chemists to engage meaningfully in science policy. The International Younger Chemists Network (IYCN), in partnership with International Union of Pure and Applied Chemistry (IUPAC), serves as a global platform for sustainable chemistry advocacy. It enables policy-relevant scholarly outputs, and international collaborative initiatives, including the ‘Global Conversation on Sustainability’ project. This annual programme coordinates global events aimed at translating sustainability research into policy-oriented dialogue.[67,68] In addition, early-career chemists can gain direct policy experience through competitive programmes such as the American Association for Advancement of Sciences (AAAS) Science and Technology Policy Fellowships. Supported by scientific societies, Including the American Chemical Society (ACS), these fellowships place scientists in government agencies to inform evidence-based policymaking.[69]

At the European level, the European Chemical Society (EuChemS) through the European Young Chemists' Network (EYCN) creates explicit pathways for early-career chemists to influence EU policy. Through participation in policy dialogues, advocacy campaigns and targeted science policy training, they contribute to shaping regulations on sustainable chemistry and chemical safety.[39] Another institution contributing to the science policy enabling early-career chemists in Europe and globally is the International Sustainable Chemistry Collaborative Centre (ISC3). Based in Germany, it provides complementary global engagement opportunities through its Sustainable Chemistry Club, training programmes and science policy capacity-building initiatives, which are accessible to early-career chemists worldwide.[70] These European organisations maintain networks with several other entities, including the Association of Southeast Asian Nations Young Scientists Network (ASEAN YSN), Asian Young Scientist (AYS) Fellowship, and the African Academy of Sciences (AAS). These networks enable early-career chemists to contribute to policy dialogues and influence the development of emissions standards, chemical regulations and sustainability frameworks in their respective regions.[71–73]

Table 1 Overview of challenges and enablers for the engagement of early-career chemists in sustainable chemistry

Challenges	Enablers
Highly formalised and hierarchical structures	● Lateral entry into policy making spaces through intergovernmental spaces (for example, UN MGCY) and global youth networks (for example, chemicals and waste youth platform) ● Establishment of spaces for the engagement of early-career chemists in regional and sub-regional policy-making (for example, council for african youth in minerals; ASMS)
Limited training and mentorship opportunities	● Establishment of science policy training platforms to prepare early-career scientists for future leadership (for example, the dedicated segments for science policy engagement of IYCN, EYCN, EU joint research centre, ISC3)
Lack of orientation and credibility to address regional policy and strategy needs	● Adaptation of chemical education curricula to local and regional needs ● Design of events and activities that provide exposure and access to early-career chemists to the policy-making paradigms
Negative political environment	● Establishment, development and compliance of effective stakeholder engagement frameworks at the intergovernmental level
Diverging funding priorities	● Promotion of innovative financing and engagement mechanisms to strengthen science policy interface (for example, NITI Aayog's programme for young professionals in frontier technologies, AAAS science and technology fellowship programme)
Personal perceptions	● Activity-based science policy training programmes aimed to build confidence among early-career chemists in science policy (for example, science policy training by ISC3)
Cultural and systemic prejudices	● Open dialogue instances between early-career scientists and policy stakeholders

Furthermore, by engaging with youth-focused policy bodies such as the IYCN, the Chemicals and Waste Youth Platform, and the United Nations Major Group for Children and Youth (UN MGCY), early-career chemists gain direct avenues to influence environmental governance.[67,74,75] Through advisory roles, contributions to circular economy strategies and participation in expert panels, early-career chemists can shape environmental regulations and sustainability initiatives.[76,77] Beyond these formal youth platforms, engagement pathways include competitive policy fellowships, expert consultations and grassroots advocacy work. Building capacity through policy-brief development and science policy internship programmes will equip early-career chemists with invaluable experience to translate technical knowledge into actionable recommendations,[78] which ensures that scientific evidence informs policy decisions.

As global priorities increasingly focus on sustainable economic growth and development, chemists represent an important stakeholder group that is both impacted by and capable of influencing these policies. Their contributions range from technical solutions (such as waste valorisation and land remediation) to strengthening evidence-based arguments for sustainability in economic policy frameworks.

While Fig. 2 summarises some of the avenues discussed in this section, the understanding of the regional context in the science policy nexus is essential for expanding opportunities to foster ground-based sustainable chemistry among early-career chemists globally. To this end, the subsequent section examines how science policy engagement operates across different geographic contexts. It also identifies challenges and opportunities for adapting known mechanisms to regions where formal pathways remain limited or non-developed.

Current status of science policy engagement in diverse demographic contexts

In 2023, several members of the IYCN emphasised the importance of engaging early-career scientists in global policy making. They argued that ‘pressing global challenges… require coordinated international responses guided by evidence-informed decisions’.[79] In addition, they highlighted the critical role that scientists must play in providing insights

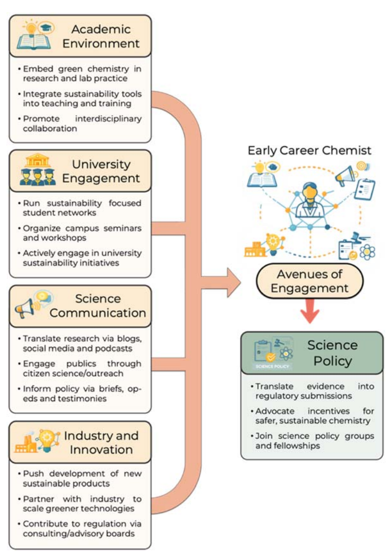

Fig. 2 Summarising avenues of engagement for early-career chemists across the globe.

throughout the decision-making process. Since then, global challenges have not only intensified but have also become increasingly intertwined with geopolitical conflicts, climate-related emergencies and a growing societal scepticism towards evidence-based science.

It is in this complex landscape that scientists have a unique opportunity to advocate for a cohesive and inclusive science policy agenda that contributes meaningfully to sustainable solutions. However, the extent and the nature of science policy engagement among chemists varies significantly across regions and even between countries. In the following sections, we highlight examples from different continents where science policy engagement has played a relevant role. We also discuss opportunities to develop a unified framework for chemists worldwide.

Europe

Science policy engagement is a priority across Europe, including both EU member and non-member states. A prominent example is the United Kingdom (UK), where science policy engagement extends well beyond academic institutions. Although universities play a significant role in connecting research with emerging policy issues,[80,81] there is also robust institutional support for researchers to directly engage with Parliament[82] and the Government.[83] Dedicated training opportunities for researchers interested in policy engagement have been established,[84,85] demonstrating a systemic approach to fostering dialogue between science and policy.

The Netherlands offers another illustrative model.[86] Here, the Ministry of Education, Culture and Science[87] is responsible for science policy, overseeing funding for higher education and research institutions, while also legislating and engaging in dialogue with the scientific community. Innovation policy, meanwhile, is coordinated by the Ministry of Economic Affairs and Climate.[88] This distributed but coordinated approach showcases a pluralistic model of science policy engagement. In this approach, multiple governmental bodies work together to support evidence-informed decision-making, which is not relegated to governmental establishments. Here, Utrecht University hosts the Institute for Sustainable and Circular Chemistry. Through both fundamental and applied chemistry research, it adopts 'a systems approach to the sustainability transition, reaching out across disciplines using chemistry as a bridging and key enabling science'.[89]

Another example of science policy engagement efforts outside governmental establishments and higher education institutions can be found in Germany, where the ISC3 is based. It provides global capacity-building programmes, as noted in the previous section. Here, the German Chemical Society (GDCh) established its Division of Sustainable Chemistry 'because the contribution of chemistry to sustainable development is becoming increasingly important worldwide'. Moreover, the GDCh is currently implementing its Sustainability Strategy 2030 to embed sustainability within all their processes, with the aim of providing information, creating solutions and contributing to sustainable action in science, business and politics.[90]

Science policy engagement efforts in this region also operate at the continental level. In this context, most scientific advisory groups are constituted primarily by senior experts. With the certainty that political advice from early-career scientists could contribute positively to political decisions through their expertise and diverse perspectives, the EYCN collaborated with the EuChemS 'to create a platform for young chemists to more closely interact with policy-makers in shaping policies'.[39] This collaboration derived into a detailed article regarding the possible roles of scientists in policy-making, with an overview of relevant platforms in the continent and opportunities for participation and involvement of early-career scientists. Although European approaches to science policy enabling for sustainability could be further expanded, this section focuses on science policy engagement across other continents, where this issue remains unaddressed.

The Americas

In contrast to Europe's coordinated efforts, science policy engagement across the Americas presents a more fragmented picture, with significant disparities between countries. In North America, the United States stands out due to its influence on global science and policy.

A founding member of both the Group of Seven (G7)[91] and North Atlantic Treaty Organization (NATO),[92] the US has recently experienced significant political shifts at the federal level,[93–95] underscoring ongoing tensions around the role of science in policymaking.[96] These shifts have generated substantial debate regarding the most effective approaches to preserving science-informed decision-making in complex political environments, both nationally and internationally.[97–101] However, such dynamics are not unprecedented in US history.[102]

Therefore, both universities and non-profit organisations (NPOs) have increasingly stepped in to fill the gaps and advocate for science policy engagement. Higher education institutions have played a leading role in advancing agendas related to climate change[103] and sustainability agendas.[104] However, they are currently facing intensified scrutiny from the government,[105–107] which may hinder their ability to advocate freely and effectively.

On the other hand, NPOs provide examples of sustained collaboration with stakeholders that are invested in science policy engagement and the pursuit of a sustainable future. One such example is Beyond Benign,[108] which has established partnerships with companies such as Merck[109] and Dow Chemicals[110] to equip educators with tools, training and support that embed green chemistry into the chemistry curriculum at all educational levels. However, recent developments suggest that NPOs may soon face pressures similar to those currently affecting universities. This is in view of non-profit leaders in the US expressing concern over potential political targeting following the advancement of a controversial tax measure in Congress.[111]

Countries in Central America, on the other hand, are often overlooked in science policy engagements due to a history of democratic backsliding,[112,113] corruption[114–116] and gang-related violence.[117–119] Moreover, disparities in development across the region makes it difficult to harness scientific expertise for policymaking and sustainable development.[120] This is only accentuated by the limited academic attention to a region that hosts between 5 and 12% of the world's biological diversity.[121]

An example of this is Guatemala, the largest economy in the region, yet small in both population and geographic area. Guatemala has experienced a long-standing outflow of its advanced human capital. This forced migration has weakened governmental and economic capacities, hampering science policy engagement at scale.[122] As a result, progress relies on the individual efforts of academics who remain in the country,[123] supported by NPOs and international chemical associations.[124,125] These encouraging efforts serve as a seedbed for early-career chemists who may view science policy making as a meaningful path that leads to a sustainable future.

Costa Rica, on the other hand, is prominent as a regional example. Known for its ecotourism, the country was able to reverse deforestation by outlawing indiscriminate logging in 1996 (ref. 126) and introducing the Payments for Environmental Services (PES)[127] Program the following year. While these achievements are commendable, there is currently no evidence of a coordinated, large-scale science policy engagement that could position the country as a regional sustainability leader.[128] For this to take place, stronger involvement of higher education institutions is essential. Their participation could help bridge policy-making with strategic socioeconomic empowerment, amplifying Costa Rica's current sustainability efforts.

In South America, disparities in development are also evident across countries. In contrast to Central America, this region, although with notable exceptions, generally features stronger economies, more established governmental institutions and robust higher education systems. A prominent example is Brazil, which is a country that contains 60% of the Amazon rainforest in its territory[129] and is a member of the Brazil, Russia, India, China and South Africa (BRICS) organization.[130] Brazil hosted the 30th Conference of the Parties to the UN Framework Convention on Climate Change (COP30) recently[131] and is recognised as a pioneer in biofuel development.[132] However, this long-standing and ambitious public policy has not been free of criticism, particularly regarding its true sustainability.[133,134] Critiques have also been directed to governmental branches, suggesting that, with exception of the Ministry of Environment and Climate Change, policy activities may not be fully aligned with the sustainability goals articulated in global agreements.[135,136] These statements have implications that extend beyond national frontiers.

Chile faces a similar problem. Although smaller in size and global influence, the country is highly exposed and vulnerable to a variety of natural disasters[125,126,137,138] and climate change-related events.[139,140] In response, the country has taken several science-informed actions. A standing example is the Soil Law Project, that was approved in 2022, which establishes a framework for the sustainable use of soil.[141] What makes this law particularly notable is its collaborative drafting process: it was co-written by approximately 50 individuals, including academics and professionals in soil science, and was sponsored by the Senate's Agriculture Commission.[142] This initiative exemplifies science policy synergy and demonstrates how multistakeholder collaboration can yield sustainable legislation.

Nevertheless, such collaborative policymaking remains the exception rather than the norm. A contrasting case is the implementation of Chile's National Lithium Strategy,[143] where tensions between environmental and economic priorities have placed the country in a difficult position.[144] While the tight decision-making timelines are far from ideal, this situation offers a valuable opportunity for academic and industrial stakeholders to engage and contribute science-based, balanced solutions that reconcile sustainability with economic development.

Africa

Africa's dynamic and youthful population, with over 70% Sub-Saharan Africans being under 30 years old, represents one of the most powerful assets in the continent for driving science policy engagement.[145] Across the region, early-career chemists and scientists are emerging as key actors in shaping sustainable futures through evidence-informed advocacy, policy participation and innovation.[146]

A significant area for youth-led engagement is critical mineral resources governance. Africa holds vast reserves of cobalt, lithium, tantalum and other rare earth elements, which are raw materials that are essential to the global green energy transition.[147,148] However, the continent's extractive landscape is deeply shaped by historical patterns of exploitation and control. From the colonial-era extraction economies established by European powers to contemporary neo-colonial dynamics, the governance of mineral resources continues to be influenced by powerful external actors. China's Belt, Road Initiative and the Forum on China-Africa Cooperation (FOCAC), the US-led Mineral Security Partnership and substantial investments from the UK, EU, Canada, Australia and South Korea all play a role in defining extraction priorities and terms of engagement. These dynamics create both opportunities such as infrastructure development and market access, and serious risks including environmental degradation, human rights violations, loss of sovereignty over natural resources, debt dependency, displacement of local communities and financing conflicts (issues well-documented in parts of West and Southern Africa).[149,150] These tensions have prompted a wave of African-led responses. Recognising both the potential and the risks, African institutions are influencing the shaping of a more objective and sustainable extractive future. The African Minerals Development Centre, a specialised agency of the African Union,[151] has developed a strategy 'for the just transition and decarbonising future'. This framework promotes regional cooperation, investment mobilisation and policy harmonisation to ensure that mineral development is both equitable and sustainable.[152]

Youth have also been mobilised around these issues. The formation of the Council for African Youth in Minerals reflects a new generation of leadership, in which early-career chemists and scientists have committed to shaping sustainable mineral governance. They are reimagining extractive industries through the lens of African priorities and knowledge systems. This initiative aims to foster collaboration between early-career professionals and African minerals institutions, by focusing on promoting local content development and socio-economic advancement in a borderless, integrated continent.[153]

Beyond mineral governance, the management of hazardous waste and chemicals is another urgent issue for which science policy engagement is critical. Africa has long been a destination for discarded electronic materials and pre-owned equipment from the developed world.[154–156] This pattern persists despite international agreements such as the Basel Convention on the Control of Transboundary Movement of Hazardous Wastes and their Disposal.[157,158] This environmental injustice has catalysed a new wave of youth activism. African youth are emerging as key agents of social and environmental change. A leading initiative is the African Youth Alliance for Chemicals and Waste,[159] a pan-African coalition that empowers and mobilises early-career professionals to co-create science-based solutions, contribute to policy dialogues and advocate for responsible chemicals governance across the continent.

Together, these youth-led initiatives reflect a broader continental shift: from externally imposed solutions to homegrown strategies that link science, sustainability and self-determination. As Africa continues to navigate a global landscape marked by climate urgency and shifting geopolitical interests, its early-career chemists are well-positioned to reshape the continent's policy future in ways that are objective, inclusive and grounded in African realities.

Asia

The science policy landscape in the Asian context is noted to be quite heterogeneous and complex.[160,161] Historical and traditional intricacies, regional geopolitical dynamics and socioeconomic attributes have played and continue to play a key role in shaping the science policy interface in the region.[161–163] This evolving engagement is influenced by a dynamic interplay of these factors, which differ considerably between countries. Countries such as Japan, China, Singapore, Taiwan and South Korea are often described as having a more developed science policy interface owing to their sustained investments in education and R&D ecosystems, strong public-private partnerships and well-established innovation cultures. In contrast, transitioning and emerging economies such as India, Bangladesh and Uzbekistan continue to face challenges in strengthening science policy engagement often due to capacity constraints and underinvestment in research infrastructure.[160,161,164,165]

Southeast Asian countries have particularly engaged in science policy interface through international science policy fellowships, such as the ASEAN Science and Technology Fellowships (2014–2020), which led to the betterment of the science policy interface in Southeast Asian countries, namely Cambodia, Indonesia, Malaysia, Myanmar, Philippines, Thailand and Vietnam.[166] The operational management of the fellowship was undertaken by the ASEAN Foundation, an institutional body of the ASEAN, with funding provided by the United States Agency for International Development (USAID).[167,168] Modelled after the AAAS Science and Technology Fellowship Program, the selected early and mid-career scientists were placed within host ministries of their respective countries for one year, where they researched policy-relevant issues, aiming to strengthen science policy interface and cross-border collaboration.[168,169] Although the programme closed in 2020, similar partnership-based engagements continue to take place.[170–172] However, these newer international programmes are characterised by a relatively higher involvement of universities and research centres than of policy-makers themselves.

In addition to these programmes, broad-level initiatives such as the Asia Science Mission for Sustainability (ASMS), which is offered by the International Science Council, also seem to strengthen the interface. It promotes integrated and evidence-based solutions aligned with the regional needs through pilot projects, capacity-building initiatives and knowledge-sharing approaches.[173] International Science Council is a collective of research organisations which leverages its network in Asia to run pilot projects in Asia as part of the ASMS.

Beyond the programmes discussed above, national-level initiatives have been established, to support decentralised models of science-based governance. For instance, the Government of India's planning wing, National Institute for Transforming India (NITI), engages young professionals to serve at district and block-level initiatives on frontier technologies.[174,175]

It is to be noted, however, that the priorities for transitioning and emerging economies, which constitute most of the Asian region, are inclined towards fulfilling the basic needs of the population and addressing certain strategic matters rather than advanced issues of science policy engagement.[161,165] The overall scenario clearly indicates that regional politics currently plays a relatively greater role in enhancing science policy engagement, pointing to the need for broader stakeholder engagement in this context.[161]

Oceania

The chemical science policy nexus remains underdeveloped across much of the continent; however Australasia represents a notable exception.[176] In Australia, platforms such as the Future Earth Australia initiative, hosted by the Australian Academy of Science;[177] the Green and Sustainable Chemistry Division of the Royal Australian Chemical Institute;[178] and Chemistry Australia play a crucial role in fostering sustainable chemistry across the region, providing significant avenues of engagement for early-career chemists.[177,179] In fact, Australia has made significant advances in chemical management, with a national framework[180] in place since 2007 guiding chemicals risk assessments and management. In conjunction with this, in 2023, the country developed a National Plan of Action for the Global Framework on Chemicals (GFC)[181] for sound management of chemicals and waste, which is already in effect. A similar plan was put in place in New Zealand, in which the Hazardous Substances and New Organisms Act 1996 (ref. 182) also recognises the issues associated with chemical safety and environmental protection. Moreover, these paradigms are continuously evolving, in alignment with international policies and standards.[183,184] A strong policy and regulatory landscape of this sort in the context of chemicals management allows for the ratification of sustainable chemistry measures. This opens avenues for the engagement of early-career chemists to meet the capacity and R&D needs. An example of such an avenue is the Centre for Green Chemical Science of the University of Auckland,[185,186] where a wide range of interdisciplinary research endeavours are conducted to address the needs of the emerging landscape of sustainable chemistry. It offers substantial opportunities for early-career chemists in developing sustainable chemistry and science policy.

In other regions of Oceania, science policy engagement is currently evolving with a particular focus on marine and ocean sustainability. It includes the addressing of the issues related to plastic pollution, the integration of indigenous and Western science, and prioritisation of nature-based solutions, among others.[187–189] The engagement is majorly spearheaded for regional coordination and technical support by the Secretariat of the Pacific Regional Environment Programme (an independent intergovernmental organisation of the Pacific Nations).[190] However, the challenges addressed by chemical sciences are intrinsically embedded within the region's interconnected socio-environmental and economic concerns (for example, management of plastic waste for ocean sustainability,[191] and nature-based solutions for environmental chemistry[192,193]) and therefore, such interlinkages can be explored and leveraged to improve the science policy interface from a chemical science perspective in the oceanic region.

This succinct yet detailed analysis illustrates how heterogeneous science policy engagement highlights both challenges and opportunities for chemists in developing science policy aligned with the SDGs. Such engagement, however, depends on the regional context in which sustainable chemistry is implemented. This section in this perspective article has enabled the compiling of a series of resources that conceives a fruitful science policy interface in the context of sustainable chemistry, which can be found in the SI (Table S1). Moreover, we want to enrich this regional analysis with the next section, in which we propose how a systemic pathway can be developed, with the aim of bridging the regional challenges and enablers.

Bridging regional challenges and enablers: developing a systemic pathway for early-career chemist participation in sustainable chemistry

Policy making spaces and networks, by tradition and design, have been highly hierarchical, bureaucratic and formal, posing significant entry barriers for early-career chemists.[79] This structural challenge is compounded by disparity between the well-established modus operandi of policy making and scientific spaces.[39] On the other hand, academic curricula presents a broad scope of study, presenting several opportunities for specialisation in scientific areas such as sustainability. However, they place a limited emphasis on bridging this knowledge with science policy, hinders the future engagement of early-career chemists at the science policy interface.[79,194,195] This issue is particularly concerning in countries where the involvement of early-career chemists is minimal, or formal training on science policy is absent and mentorship opportunities adapted to their regional needs are lacking. While opportunities exist in Europe[196] and the US,[197] adaptation to local frameworks requires support that is often unavailable to interested stakeholders.[79]

This analysis is aligned with the observations of Dobbelaar *et al.*[69] who scrutinised the data obtained from a 2020 survey that was conducted by the Young Chemistry Forum of the German Chemical Society (GDCh-JCF). Here, the data obtained from over 500 chemists across 46 countries identified hierarchical policy structures, limited training opportunities and curricula-policy misalignment as critical barriers. Building on these insights and our regional analysis of current science policy landscapes, we identify concrete pathways to address these challenges systematically. Overcoming these barriers requires transformational shifts at the science policy interface across local, national, regional and global organisations. But to pass them, it must be kept in mind that these shifts must be cultural (embracing youth voices and intergenerational equity), functional (establishing dedicated platforms for new voices) and structural (ensuring equitable access to resources, networks and training for early-career chemists).[198,199] At the same time, existing structures, organisations and networks that already provide opportunities for lateral entry of early-career chemists into policy-making spaces must be leveraged and strengthened. In Table 1, we summarise key challenges alongside potential enablers that address each barrier, many of which are already operational in specific geographic contexts.

The regional analysis in the previous section demonstrates how the challenges and enablers outlined here manifest differently across geographic contexts, informing the adaptation of engagement mechanisms. In light of this, we have synthesised these regional variations into five critical engagement mechanisms: Interdisciplinary and Collaborative Research, Institutional and Policy Engagement Pathways, Engagement through NGOs and Civil Society Platforms, Technical Contribution through R&D Institutions and Mechanisms within Intergovernmental and Multilateral Organisations. All these mechanisms are listed on Table 2, indicating how each can be operationalised across different geographical contexts.

While early-career chemists drive engagement at the science policy interface, systemic transformation depends on the coordinated action from multiple stakeholders. The European model is used here to exemplify how formal training programmes and institutional pathways create sustainable engagement ecosystems. In such contexts, universities that successfully integrate early-career chemists into policy work typically provide dedicated science-policy training, foster cross-departmental collaboration and establish formalised pathways

Table 2 Detailed overview of the framework for engaging early-career chemists in sustainable chemistry from science policy perspectives

Key elements of the framework	Objectives	Actions
Interdisciplinary and collaborative research	Empower early-career chemists to contribute meaningfully to sustainability challenges through integrated scientific approaches	● Promote interdisciplinary curricula in academic institutions that combine chemistry with environmental science, systems thinking and sustainability ● Facilitate collaborative research platforms that involve chemists, engineers, social scientists and policy experts ● Support student-led research initiatives on sustainability chemistry topics (for example, green synthesis, circular economy, pollution control)
Institutional and policy engagement pathways	Create structured avenues for early-career chemists to participate in policy and decision-making processes	● Establish youth science advisory councils at national and international levels to integrate early-career chemists into policymaking bodies ● Engage with science policy mechanisms such as the intergovernmental science policy panel on chemicals, waste and pollution ● Promote internships and fellowships in ministries, regulatory bodies and international agencies working on sustainability and chemicals management
Engagement through NGOs and civil society platforms	Enable active participation of early-career chemists in societal dialogue and sustainability advocacy	● Partner with NGOs to implement community projects related to sustainable chemistry (for example, clean water, waste valorisation) ● Encourage youth-led advocacy and communication on the role of chemistry in achieving the SDGs ● Support participation in multi-stakeholder forums, grassroots mobilisations and global youth movements for climate and environmental justice
Technical contribution through R&D institutions	Leverage national and international R&D institutions as channels for early-career chemists to drive innovation in sustainability	● Provide research internships and visiting scholar programmes in public and private research centres focused on green technologies ● Encourage contributions to global scientific assessments and reports through youth-focused calls or expert working groups ● Foster innovation hubs and incubators to support youth-led start-ups in sustainable materials, energy and chemical alternatives
Mechanisms within intergovernmental and multilateral organisations	Strengthen formal mechanisms to include early-career chemists in international science policy platforms	● Institutionalise youth observer roles or consultative statuses in bodies such as UNEP, OECD, GFC and IUPAC ● Facilitate access to intergovernmental conferences (for example, Stockholm Convention COPs, UN environment assembly) through youth delegations ● Develop capacity-building programmes co-hosted by intergovernmental organisations (IGOs) to equip early-career chemists with science policy negotiation and diplomacy skills

linking research and policy. On the other hand, senior policymakers and advisory bodies in regions with robust ecosystems have established designated spaces for early-career input, integrating emerging perspectives with established expertise. Furthermore, the integration of civil society organisations and R&D institutions that successfully engage youth perspectives have reduced hierarchical barriers and created accessible entry points. In addition, intergovernmental and multilateral organisations are increasingly diversifying advisory bodies and knowledge-brokerage systems, recognising that early-career perspectives strengthen evidence-based decision-making. Establishing mechanisms for monitoring, evaluation and feedback enables continuous improvement of engagement pathways for future actors. Nevertheless, following the analysis undertaken for this perspective, it is evident that tensions exist between rhetoric and the realities faced by early-career scientists in relation to science policy engagement. Despite widespread knowledge of the value of diverse perspectives, science policy structures remain fundamentally hierarchical, with decision-making authority concentrated among senior gatekeepers. The proliferation of youth engagement platforms might create the illusion of inclusion, while leaving power structures unchanged.

If the aim is a transformational shift in science policy engagement, this warrants critical reflection. Institutions aiming for a broadening of their current members should also question continued reliance on hierarchical structures that may have been effective in the past, but are increasingly outdated. Although such a question cannot be easily answered, opening spaces for early-career chemists who are interested in sustainable chemistry and who may see science policy engagement as an avenue to influence their regional context represents only an initial step. Senior stakeholders must also be open to contemporary perspectives, institutions must be involved in governmental instances of participation, and students and academics must be encouraged to engage with science policy. In addition, interdisciplinary initiatives must be financed with the same seriousness afforded to traditional research. Otherwise, early-career engagement will remain performative rather than transformative.

Aligned with the recent editorial written by Mahaffy and Garcia-Martinez,[200] this perspective not only examines how early-career chemists can engage with science policy in sustainable chemistry, but also identifies what is required to achieve such engagement. Previous work, including the Viewpoint article by Dobbelaar *et al.*,[68] has articulated key thematic challenges, opportunities, and actionable pathways. Building on this foundation, the present analysis examines how these challenges and opportunities are shaped by regional, institutional, and socio-political contexts. Through region-specific examples of engagement mechanisms, we explore conditions that influence implementation and adaptation across diverse settings, particularly where formal science policy pathways remain limited.[38,66,67] Taken together, these regionally grounded insights are situated within a systemic framework, illustrating circumstances under which engagement aspirations may translate into context-sensitive implementation pathways. In particular, they highlight how practitioners in under-resourced contexts can draw on established mechanisms and adapt them to local realities, contributing to a broader capacity for science-informed policy development. While evidence for effective approaches already exists, further reflection is required on how, where and by whom such mechanisms are mobilised within evolving governance landscapes.

Conclusions

Early-career chemists are uniquely positioned to catalyse sustainable transformations in chemistry by combining technical expertise with intergenerational urgency. Their active engagement across academia, industry, policy and society is not merely desirable, but essential in the current milieu. As illustrated in this perspective, regional disparities in science policy engagement create both challenges and opportunities. Strengthening global and local cooperation, fostering openness among senior stakeholders to emerging perspectives and increasing institutional involvement in governmental processes are essential. Equally important are encouraging students and academics to participate in those instances, along with the financing of interdisciplinary initiatives, while embedding sustainability into early-career training. The drive to achieve this is critical for building a resilient and inclusive future for the chemical sciences. What remains is the urgent task of aligning structures, resources and perspectives to make it a reality.

Author contributions

The manuscript was written through the contributions of all authors. All authors have approved the final version of the manuscript. Conceptualisation: Lovish Raheja, Francisca J. Benítez, José Ferraz-Caetano, Maulline G. Leviev, Aanchal Saxena, Anna Isabel Becker; visualisation: Lovish Raheja, José Ferraz-Caetano, Aanchal Saxena; writing – original draft: Lovish Raheja, Francisca J. Benítez, José Ferraz-Caetano, Maulline G. Leviev, Aanchal Saxena, Anna Isabel Becker; writing – review and editing: Lovish Raheja, Francisca J. Benítez, José Ferraz-Caetano, Maulline G. Leviev.

Conflicts of interest

There are no conflicts to declare.

Abbreviations

US EPA	United states environmental protection agency
EC	European commission
EU	European union
SDGs	Sustainability development goals
OSTP	Office of science and technology policy
LCA	Life-cycle assessment
R&D	Research and development
IYCN	International younger chemists network
IUPAC	International union of pure and applied chemistry
AAAS	American association for advancement of sciences
ACS	American chemical society
EuChemS	European chemical society
EYCN	European young chemists' network
ISC3	International sustainable chemistry collaborative centre
YSN	Young scientists network
ASEAN	Association of southeast asian nations
AYS	Asian young scientist
AAS	African academy of sciences
UN	United nations
MGCY	Major group for children and youth
UK	United kingdom
GDCh	Gesellschaft deutscher chemiker (German chemical society)
G7	Group of seven
NATO	North atlantic treaty organization
NPOs	Non-profit organisations
PES	Payments for environmental services
FOCAC	Forum on china-africa cooperation
USAID	United states agency for international development
ASMS	Asia science mission for sustainability

NITI	National institute for transforming india
GFC	Global framework on chemicals
JCF	Junges chemie forum (young chemistry forum)
NGOs	Non-government organisations
IGOs	Intergovernmental organisations

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this perspective article.

Supplementary information (SI): compilation of resources that conceives a fruitful science policy interface in the context of sustainable chemistry. See DOI: https://doi.org/10.1039/d5su00550g.

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References

1 W. Steffen, K. Richardson, J. Rockström, S. E. Cornell, I. Fetzer, E. M. Bennett, R. Biggs, S. R. Carpenter, W. De Vries, C. A. De Wit, C. Folke, D. Gerten, J. Heinke, G. M. Mace, L. M. Persson, V. Ramanathan, B. Reyers and S. Sörlin, Planetary boundaries: Guiding human development on a changing planet, *Science*, 2015, **347**, 1259855.
2 M. Lawrence, T. Homer-Dixon, S. Janzwood, J. Rockstöm, O. Renn and J. F. Donges, Global polycrisis: the causal mechanisms of crisis entanglement, *Glob. Sustain.*, 2024, 7, e6.
3 P. B. Larsen and K. Tararas, Editorial: Enhancing the right to science: the triple planetary crisis and the need for comprehensive approaches, *Front. Sociol.*, 2024, **9**, 1406640.
4 R. Maurya, S. Madan, M. Kumari and B. Sadhiyan, in *Practice, Progress, and Proficiency in Sustainability*, ed. A. K. Rathoure, IGI Global, 2024, pp. 117–136.
5 R. G. Stokes and C. W. Miller, in *The Routledge Companion to the Makers of Global Business*, Routledge, 2019.
6 A. Badr and H. H. El-Shazly, Climate Change and Biodiversity Loss: Interconnected Challenges and Priority Measures, *Int. J. Environ. Sci.*, 2024, **29**, 69–78.
7 I. Herrmann, The Chemical Industry's Key Role In A Nature-Positive Future, https://www.oliverwyman.com/our-expertise/insights/2024/may/chemicals-industry-role-nature-positive-future.html, accessed 5 May 2025.
8 International Energy Agency, Chemicals, https://www.iea.org/energy-system/industry/chemicals, accessed 5 May 2025.
9 J. Tickner, K. Geiser and S. Baima, Transitioning the Chemical Industry: The Case for Addressing the Climate, Toxics, and Plastics Crises, *Environment*, 2021, **63**, 4–15.
10 A. Nabera, I.-R. Istrate, A. José Martín, J. Pérez-Ramírez and G. Guillén-Gosálbez, Energy crisis in Europe enhances the sustainability of green chemicals, *Green Chem.*, 2023, **25**, 6603–6611.
11 G. Sigmund, M. Ågerstrand, A. Antonelli, T. Backhaus, T. Brodin, M. L. Diamond, W. R. Erdelen, D. C. Evers, T. Hofmann, T. Hueffer, A. Lai, J. P. M. Torres, L. Mueller, A. L. Perrigo, M. C. Rillig, A. Schaeffer, M. Scheringer, K. Schirmer, A. Tlili, A. Soehl, R. Triebskorn, P. Vlahos, C. vom Berg, Z. Wang and K. J. Groh, Addressing chemical pollution in biodiversity research, *Global Change Biol.*, 2023, **29**, 3240–3255.
12 R. Naidu, B. Biswas, I. R. Willett, J. Cribb, B. Kumar Singh, C. Paul Nathanail, F. Coulon, K. T. Semple, K. C. Jones, A. Barclay and R. J. Aitken, Chemical pollution: A growing peril and potential catastrophic risk to humanity, *Environ. Int.*, 2021, **156**, 106616.
13 R. Prăvălie, Exploring the multiple land degradation pathways across the planet, *Earth-Sci. Rev.*, 2021, **220**, 103689.
14 A. S. Kolawole and A. O. Iyiola, in *Sustainable Utilization and Conservation of Africa's Biological Resources and Environment*, ed. S. C. Izah and M. C. Ogwu, Springer Nature, Singapore, 2023, pp. 377–409.
15 H. Flerlage and J. C. Slootweg, Modern chemistry is rubbish, *Nat. Rev. Chem.*, 2023, **7**, 593–594.
16 OECD, *Sustainable Chemistry: Evidence on Innovation from Patent Data*, OECD, 2011.
17 M. Lancaster, *Green Chemistry: an Introductory Text*, The Royal Society of Chemistry, 3rd edn, 2016.
18 M. Burmeister, S. Schmidt-Jacob and I. Eilks, German chemistry teachers' understanding of sustainability and education for sustainable development—An interview case study, *Chem. Educ. Res. Pract.*, 2013, **14**, 169–176.
19 C. Blum, B. Zeschmar-Lahl, E. Heidbüchel, H. C. Stolzenberg, K. Kümmerer, A. Becker and H. Friege, Metrics are the key: development of criteria and indicators for measuring sustainability in international chemicals management, *RSC Sustainability*, 2025, **3**, 4724–4745.
20 M. A. Murphy, Early Industrial Roots of Green Chemistry: International "Pollution Prevention" Efforts During the 1970s and 1980s, *Chem. Int.*, 2021, **43**, 21–25.
21 UN, Rio Declaration on Environment and Development, *United Nations Conference on Environment and Development*, Rio de Janerio, 1992.
22 EU Council, *Directive 96/61/EC of 24 September 1996 Concerning Integrated Pollution Prevention and Control*, 1996.

23 P. T. Anastas and J. C. Warner, *Green Chemistry: Theory and Practice*, Oxford University Press, Oxford, New York, 2000.
24 C. A. Marques and A. A. S. C. Machado, Environmental Sustainability: implications and limitations to Green Chemistry, *Found. Chem.*, 2014, **16**, 125–147.
25 W. R. Stahel, The circular economy, *Nature*, 2016, **531**, 435–438.
26 W. R. Stahel, The product life factor, *An Inquiry into the Nature of Sustainable Societies. The Role of the Private Sector*, Houston Area Research Centre, Houston, 1982, pp. 72–105.
27 T. Keijer, V. Bakker and J. C. Slootweg, Circular chemistry to enable a circular economy, *Nat. Chem.*, 2019, **11**, 190–195.
28 R. De Man, in *The Impossibilities of the Circular Economy*, ed. H. Lehmann, C. Hinske, V. de Margerie and A. Slaveikovka Nikolova, Routledge, 2023, pp. 3–10.
29 M. Faber, How to be an ecological economist, *Ecol. Econ.*, 2008, **66**, 1–7.
30 M. Giampietro, in *The Impossibilities of the Circular Economy*, ed. H. Lehmann, C. Hinske, V. de Margerie and A. Slaveikova Nikolova, 2022, pp. 37–47.
31 K. Kümmerer, Sustainable Chemistry: A Future Guiding Principle, *Angew. Chem., Int. Ed.*, 2017, **56**, 16420–16421.
32 M. Weaver, A. P. Fonseca, H. Tan and K. Pokorna, Systems thinking for sustainability: shifting to a higher level of systems consciousness, *J. Oper. Res. Soc.*, 2025, 1–14.
33 E. Vuorio, J. Pernaa and M. Aksela, A Pedagogical Model for Teaching Systems Thinking in a Sustainable Chemistry Course: A Design-Based Research Approach, *J. Chem. Educ.*, 2025, **102**, 3878–3892.
34 M. Orgill, S. York and J. MacKellar, Introduction to Systems Thinking for the Chemistry Education Community, *J. Chem. Educ.*, 2019, **96**, 2720–2729.
35 P. Bhandari, J. Gong, C. Boyle, K. M. Y. Law and D. Creighton, Harnessing the value of data using the systems thinking approach, *Water Res.:X*, 2025, **28**, 100385.
36 K. B. Aubrecht, M. Bourgeois, E. J. Brush, J. MacKellar and J. E. Wissinger, Integrating Green Chemistry in the Curriculum: Building Student Skills in Systems Thinking, Safety, and Sustainability, *J. Chem. Educ.*, 2019, **96**, 2872–2880.
37 K. M. D. Reyes, K. Bruce and S. Shetranjiwalla, Green Chemistry, Life Cycle Assessment, and Systems Thinking: An Integrated Comparative-Complementary Chemical Decision-Making Approach, *J. Chem. Educ.*, 2023, **100**, 209–220.
38 A. R. McCluskey, M. Rivera and A. S. J. S. Mey, Digital skills in chemical education, *Nat. Chem.*, 2024, **16**, 1383–1384.
39 T. John, M. Cieślak, D. Vargová, S. M. Richardson, V. Mougel and J. V. Milić, The Role of Early-Career Chemists in European Policy-Making, *Chem.–Eur. J.*, 2021, **27**, 6359–6366.
40 L. Marcelino, J. Sjöström and C. A. Marques, Socio-Problematization of Green Chemistry: Enriching Systems Thinking and Social Sustainability by Education, *Sustainability*, 2019, **11**, 7123.
41 European Commission, *Chemicals Strategy for Sustainability: towards a Toxic-free Environment*, 2020.
42 White House Office of Science and Technology Policy, *Sustainable Chemistry Report: Framing the Federal Landscape*, Executive Office of the President of the United States, 2023.
43 *International Sustainable Chemistry Collaborative Centre (ISC3)*, 2021.
44 UNEP, Nations come together to establish new Intergovernmental Science-Policy Panel on Chemicals, Waste and Pollution, https://www.unep.org/news-and-stories/press-release/nations-come-together-establish-new-intergovernmental-science-policy, accessed 30 June 2025.
45 C. Choe, J. A. Moon, J. Gu, A. Lee and H. Lim, Life cycle sustainability assessment for sustainable energy future: A short review on opportunity and challenge, *Curr. Opin. Green Sustainable Chem.*, 2024, **50**, 100974.
46 G. Mondello, R. Salomone, G. Ioppolo, G. Saija, S. Sparacia and M. C. Lucchetti, *Sustainability*, 2017, **9**(5), 827.
47 G. Egger, K. Waniek, J.-P. Schöggl, C. O. Kappe and R. J. Baumgartner, Sustainability Assessment during Early Stage Chemical Process Design: Comparing Two Different Methods of Synthesizing Noroxymorphone, *ACS Sustain. Chem. Eng.*, 2024, **12**, 18666–18678.
48 S. G. Koenig, C. Bee, A. Borovika, C. Briddell, J. Colberg, G. R. Humphrey, M. E. Kopach, I. Martinez, S. Nambiar, S. V. Plummer and others, A Green Chemistry Continuum for a Robust and Sustainable Active Pharmaceutical Ingredient Supply Chain, *ACS Sustain. Chem. Eng.*, 2019, **7**, 16937–16951.
49 L. Maxim, The Birth of Green Chemistry: A Political History, *Sci. Technol. Hum. Val.*, 2023, **50**, 144–168.
50 P. M. Falcone, S. González García, E. Imbert, L. Lijó, M. T. Moreira, A. Tani, V. E. Tartiu and P. Morone, Transitioning towards the bio-economy: Assessing the social dimension through a stakeholder lens, *Corp. Soc. Responsib. Environ. Manag.*, 2019, **26**, 1135–1153.
51 K. J. M. Matus, W. C. Clark, P. T. Anastas and J. B. Zimmerman, Barriers to the Implementation of Green Chemistry in the United States, *Environ. Sci. Technol.*, 2012, **46**, 10892–10899.
52 J. Garcia-Martinez, A. Moores, B. Subramaniam, M. A. R. Meier and P. Licence, The Muscat Declaration: A Guiding Light to Illuminate the Path of the Green and Sustainable Chemistry and Engineering Community, *ACS Sustain. Chem. Eng.*, 2025, **13**, 5796–5797.
53 P. Anastas, M. Nolasco, F. Kerton, M. Kirchhoff, P. Licence, T. Pradeep, B. Subramaniam and A. Moores, The Power of the United Nations Sustainable Development Goals in Sustainable Chemistry and Engineering Research, *ACS Sustainable Chem. Eng.*, 2021, **9**, 8015–8017.
54 K. C. Hoffman and A. P. Dicks, Incorporating the United Nations Sustainable Development Goals and green chemistry principles into high school curricula, *Green Chem. Lett. Rev.*, 2023, **16**, 2185108.
55 K. M. D. Reyes, K. Bruce and S. Shetranjiwalla, Green Chemistry, Life Cycle Assessment, and Systems Thinking:

An Integrated Comparative-Complementary Chemical Decision-Making Approach, *J. Chem. Educ.*, 2023, **100**, 209–220.
56 R. Alyousef, H. Mohammadhosseini, F. Alrshoudi, M. M. Tahir, H. Alabduljabbar and A. M. Mohamed, *Crystals*, 2020, **10**(8), 696.
57 O. Schilter, P. Schwaller and T. Laino, Balancing computational chemistry's potential with its environmental impact, *Green Chem.*, 2024, **26**, 8669–8679.
58 P. T. Anastas and M. M. Kirchhoff, Origins, Current Status, and Future Challenges of Green Chemistry, *Acc. Chem. Res.*, 2002, **35**, 686–694.
59 D. J. C. Constable, A. D. Curzons and V. L. Cunningham, Metrics to 'green' chemistry—which are the best?, *Green Chem.*, 2002, **4**, 521–527.
60 H. Lawton Smith and L. Leydesdorff, The Triple Helix in the context of global change: dynamics and challenges, *Prometheus*, 2014, **32**, 321–336.
61 V. Zuin and I. Eilks, *Green and Sustainable Chemistry Education: Nurturing a New Generation of Chemists*, UNEP, 2019.
62 *Science Literacy: Concepts, Contexts, and Consequences*, ed. C. E. Snow and K. A. Dibner, National Academies Press, Washington, D.C., 2016.
63 B. Fischhoff, Evaluating science communication, *Proc. Natl. Acad. Sci. U. S. A.*, 2019, **116**, 7670–7675.
64 A. Irwin, *Citizen Science: A Study of People, Expertise and Sustainable Development*, Routledge, London, 2002.
65 C. Mason and J. Simmons, Embedding Corporate Social Responsibility in Corporate Governance: A Stakeholder Systems Approach, *J. Bus. Ethics*, 2014, **119**, 77–86.
66 M. E. Porter and M. R. Kramer, *Harv. Bus. Rev.*, 2011, **89**(1–2), 62–77.
67 C. Sotério, J. Borges and J. G. Martínez, IUPAC and IYCN: Working Together for a Globally Sustainable Future, *Chem. Int.*, 2022, **44**, 39–45.
68 J. L. Vidal and J. Borges, The Global Conversation on Sustainability: An IYCN/IUPAC Joint Effort to Creating a Sustainable Future Worldwide, *Chem. Int.*, 2023, **45**, 10–16.
69 E. Dobbelaar, S. S. Goher, J. L. Vidal, N. K. Obhi, B. M. B. Felisilda, Y. S. L. Choo, H. Ismail, H. L. Lee, V. Nascimento, R. Al Bakain, M. Ranasinghe, B. L. Davids, A. Naim, N.-A. Offiong, J. Borges and T. John, Towards a Sustainable Future: Challenges and Opportunities for Early-Career Chemists, *Angew. Chem., Int. Ed.*, 2024, **63**, e202319892.
70 ISC3, What we do, https://www.isc3.org/page/what-we-do, accessed 18 November 2025.
71 ASM, Launching of the ASEAN Young Scientists Network (ASEAN YSN) – ASM FOCUS, https://www.akademisains.gov.my/asm-focus/launching-of-the-asean-young-scientists-network-asean-ysn/, accessed 27 May 2025.
72 Asian Young Scientist Fellowship, https://www.aysfellowship.org, accessed 27 May 2025.
73 AAS, The African Academy of Sciences (AAS), https://aasciences.africa/, accessed 27 May 2025.
74 S. Lisa, *The Chemicals and Waste Youth Platform*, Geneva Environment Network, 2025.
75 UN MGCY, Overview, https://www.unmgcy.org/about-overview, accessed 27 May 2025.
76 OECD, *OECD Urban Studies the Circular Economy in Cities and Regions Synthesis Report*, OECD Publishing, Paris, 2020.
77 *Circular Economy in Europe: Developing the Knowledge Base*, ed. European Environment Agency, Publications Office of the European Union, Luxembourg, 2016.
78 J. Lubchenco, Environmental science in a post-truth world, *Front. Ecol. Environ.*, 2017, **15**, 3.
79 T. John, K. E. Cordova, C. T. Jackson, A. C. Hernández-Mondragón, B. L. Davids, L. Raheja, J. V. Milić and J. Borges, Engaging Early-Career Scientists in Global Policy-Making, *Angew. Chem., Int. Ed.*, 2023, **62**, e202217841.
80 University of Oxford, Oxford Policy Engagement Network (OPEN), https://www.ox.ac.uk/research/using-research-engage/policy-engagement/oxford-policy-engagement-network-OPEN, accessed 16 May 2025.
81 Research & Policy Engagement – Networks of evidence and expertise for public policy, https://www.csap.cam.ac.uk/Research-Policy-Engagement/, accessed 16 May 2025.
82 UK Parliament, Research impact at the UK Parliament, https://www.parliament.uk/get-involved/research-impact-at-the-uk-parliament/, accessed 16 May 2025.
83 D. A. McLean, Routes for academic engagement with Government, https://www.gov.uk/government/publications/routes-for-academic-engagement-with-government/routes-for-academic-engagement-with-government, accessed 16 May 2025.
84 UK Parliament, Policy Engagement for Researchers, https://www.parliament.uk/get-involved/research-impact-at-the-uk-parliament/training-and-events/online-training-for-researchers/policy-engagement-for-researchers—how-to-engage-with-government-in-contrast-to-parliament/, accessed 16 May 2025.
85 UKRI, Policy engagement training programme for researchers, https://www.ukri.org/what-we-do/developing-people-and-skills/ahrc/learn-about-the-policymaking-process-with-engaging-with-government/, accessed 16 May 2025.
86 Science policy and innovation policy, https://www.rathenau.nl/en/science-figures/policy-and-structure/infrastructure-knowledge/science-policy-and-innovation-policy, accessed 19 May 2025.
87 C. en W. Ministerie van Onderwijs, Ministry of Education, Culture and Science - Government.nl, https://www.government.nl/ministries/ministry-of-education-culture-and-science, accessed 19 May 2025.
88 L. en I. Ministerie van Economische Zaken, Ministry of Economic Affairs - Government.nl, https://www.government.nl/ministries/ministry-of-economic-affairs, accessed 19 May 2025.

89 Utrecht University, Institute for Sustainable and Circular Chemistry, https://www.uu.nl/en/research/institute-for-sustainable-and-circular-chemistry, accessed 18 November 2025.
90 German Chemical Society, Sustainability as a guiding principle: Our path to the future, https://en.gdch.de/gdch/sustainability.html, accessed 18 November 2025.
91 About the G7, https://g7.canada.ca/en/g7-information/about/#members-and-presidency, accessed 14 May 2025.
92 NATO, NATO member countries, https://www.nato.int/cps/en/natohq/topics_52044.htm, accessed 14 May 2025.
93 J. Mervis, Trump orders cause chaos at science agencies, https://www.science.org/content/article/trump-orders-cause-chaos-science-agencies, accessed 14 May 2025.
94 E. Bush, A. Bendix and D. Chow, Science under siege, https://www.nbcnews.com/science/science-news/trumps-nih-budget-cuts-threaten-research-stirring-panic-rcna191744, accessed 14 May 2025.
95 B. Casselman, *The New York Times*, 2025.
96 D. Moynihan and P. Herd, Institutionalizing politicized science, *Science*, 2025, eady6128.
97 C. Cassidy, *The Guardian*, 2025.
98 R. M. Webb and L. Kurtz, in *Progress in Molecular Biology and Translational Science*, Elsevier, 2022, vol. 188, pp. 65–80.
99 D. Garisto, J. Tollefson and A. Witze, How Trump's attack on universities is putting research in peril, *Nature*, 2025, DOI: 10.1038/d41586-025-01289-4.
100 F. Schwaller, Trump's ‘assault on science’, https://www.dw.com/en/trumps-assault-on-science-bad-for-the-us-good-for-eu/a-71897988, accessed 14 May 2025.
101 H. Morin, F. Rosier, L. Sanchez, P. Santi, D. Larousserie, L. Belot and J.-B. Jacquin, How Trump's anti-science policies are impacting French research, https://www.lemonde.fr/en/science/article/2025/04/15/how-trump-s-anti-science-policies-are-impacting-french-research_6740263_10.html, accessed 14 May 2025.
102 E. Berman and J. Carter, Policy Analysis: Scientific Integrity in Federal Policymaking Under Past and Present Administrations, *J. Sci. Policy Gov.*, 2018, **13**(1).
103 R. R. Prasad, in *The Role of Higher Education Institutions in Climate Change Adaptation and Mitigation: A Case Study of Fiji and Indonesia*, ed. R. R. Prasad, Springer Nature Switzerland, Cham, 2025, pp. 63–89.
104 R. R. Prasad, in *The Role of Higher Education Institutions in Climate Change Adaptation and Mitigation: A Case Study of Fiji and Indonesia*, ed. R. R. Prasad, Springer Nature Switzerland, Cham, 2025, pp. 123–183.
105 M. C. B. Blinder and J. Swan, *The New York Times*, 2025.
106 J. S. Rosenberg, The Trump Administration's Impact on Higher Education, https://www.harvardmagazine.com/2025/05/harvard-trump-federal-funding-education-diversity-speech, accessed 19 May 2025.
107 ACE, Higher Education & The Trump Administration, https://www.acenet.edu/Policy-Advocacy/Pages/2025-Trump-Administration-Transition.aspx, accessed 19 May 2025.
108 Home, https://www.beyondbenign.org/, accessed 19 May 2025.
109 About Partnerships, https://www.beyondbenign.org/about-partnerships/, accessed 19 May 2025.
110 Beyond Benign, Beyond Benign Partners with Dow to Expand Green Chemistry in Higher Education, https://www.beyondbenign.org/news/beyond-benign-partners-with-dow-to-expand-green-chemistry-in-higher-education/, accessed 19 May 2025.
111 F. Schouten, Nonprofit leaders say they are bracing for potential targeting by the Trump administration after a controversial tax measure advances in Congress | CNN Politics, https://www.cnn.com/2025/05/17/politics/nonprofit-leaders-say-they-are-bracing-for-potential-targeting-by-the-trump-administration-after-a-controversial-tax-measure-advances-in-congress, accessed 19 May 2025.
112 S. A. McConnell, Elite Collusion and Creeping Authoritarianism in Nicaragua: Lessons on Democratic Backsliding from an Outlier Case, *Ann. Am. Acad. Polit. Soc. Sci.*, 2024, **712**, 196–210.
113 N. Bullock, Countering El Salvador's Democratic Backsliding, https://www.hrw.org/news/2023/03/21/countering-el-salvadors-democratic-backsliding, accessed 19 May 2025.
114 AFP, L'ex-président du Panama condamné pour corruption obtient l'asile en Colombie, https://www.lesoir.be/674508/article/2025-05-11/lex-president-du-panama-condamne-pour-corruption-obtient-lasile-en-colombie, accessed 19 May 2025.
115 Tico Times, Costa Rica Shows Progress in 2024 Global Anti Corruption Index, https://ticotimes.net/2025/02/11/costa-rica-shows-progress-in-2024-global-anti-corruption-index, accessed 19 May 2025.
116 Human Rights Watch, in *World Report 2025*, 2024.
117 T. Times, Costa Rica's Paradise Lost, https://ticotimes.net/2025/02/12/costa-ricas-paradise-lost-from-tourist-haven-to-drug-hub, accessed 19 May 2025.
118 Human Rights Watch, El Salvador's Cycles of Violence Through a Teenager's Eyes, https://www.hrw.org/news/2024/04/09/el-salvadors-cycles-violence-through-teenagers-eyes, accessed 19 May 2025.
119 Florida International University-Digital Communications, Guatemala's Security Challenges and the Government's Response, https://gordoninstitute.fiu.edu/news-events/the-policy-spotlight/2024/guatemalas-security-challenges-and-the-governments-response.html, accessed 19 May 2025.
120 J. A. Huete-Pérez, A. C. Hernández-Mondragón, D. S. Massey, L. M. Cumba García, B. Amadei, N. De León Sautú, M. L. Acosta, O. Asensio, J. Boright, S. Cosgrove, E. Hernández Hernández, M. López-Selva, J. L. Manfredi, F. Mondragón, J. M. Natera, O. C. Picardo Joao, A. Rivero Santos and H. O. Rocha, Catalyzing sustainable development: insights from the international workshop on STI policies and innovation systems in Central America, *Front. Res. Metr. Anal.*, 2024, **9**, 1511393.

121 J. A. Morales-Marroquín, R. Solis Miranda, J. Baldin Pinheiro and M. I. Zucchi, Biodiversity Research in Central America: A Regional Comparison in Scientific Production Using Bibliometrics and Democracy Indicators, *Front. Res. Metr. Anal.*, 2022, **7**, 898818.
122 K. Bonilla, C. S. Romero-Oliva, S. Arrechea, N. Y. Ortiz Osejo, S. Mazariegos, M. Alonzo, G. Orellana-Corrales, A. C. Del Valle and G. Montenegro-Bethancourt, Engaging the Guatemala Scientific Diaspora: The Power of Networking and Shared Learning, *Front. Res. Metr. Anal.*, 2022, **7**, 897670.
123 Youth Forum on Chemicals Governance, 2023, https://enb.iisd.org/youth-forum-chemicals-governance-2023, accessed 20 May 2025.
124 Sustainability Stars, https://www.acs.org/green-chemistry-sustainability/funding-and-recognition/sustainability-stars.html, accessed 21 May 2025.
125 Green Chemistry For Sustainability, https://chemistryforsustainability.org/, accessed 28 May 2025.
126 Forest Law (Law No.7575) – Climate Change Laws of the World, https://climate-laws.org/document/forest-law-law-no-7575_618a, accessed 21 May 2025.
127 UNFCCC, Payments for Environmental Services Program | Costa Rica, https://unfccc.int/climate-action/momentum-for-change/financing-for-climate-friendly-investment/payments-for-environmental-services-program, accessed 21 May 2025.
128 Sustainable Development Report, 2024, https://dashboards.sdgindex.org/, accessed 21 May 2025.
129 S. Zanon, Deforestation in the Amazon, http://infoamazonia.org/en/2023/03/21/deforestation-in-the-amazon-past-present-and-future/, accessed 21 May 2025.
130 About the BRICS, https://brics.br/en/about-the-brics, accessed 21 May 2025.
131 COP30 Brasil Amazônia - Português (Brasil), https://cop30.br/pt-br, accessed 21 May 2025.
132 C. Grangeia, L. Santos and L. L. B. Lazaro, The Brazilian biofuel policy (RenovaBio) and its uncertainties: An assessment of technical, socioeconomic and institutional aspects, *Energy Convers. Manage.:X*, 2022, **13**, 100156.
133 E. J. De Area Leão Pereira, L. M. Diele-Viegas and L. C. De Santana Ribeiro, GHG emissions in Brazilian Agriculture and livestock sectors and the risk to Amazonia conservation, *Eur. Phys. J. B*, 2024, **97**, 94.
134 R. Rice, A. Dias Dos Santos and S. Bryant, From green revolution to green technology: the unintended consequences of Brazil's ethanol program, *Can. J. Lat. Am. Caribb. Stud.*, 2025, **0**, 1–22.
135 *AAAS Science and Diplomacy*, 2025.
136 P. M. Fearnside and W. L. Filho, COP 30: Brazilian policies must change, *Science*, 2025, **387**, 1237.
137 Strongest earthquakes in Chile2022, https://www.statista.com/statistics/1204298/earthquake-magnitude-chile/, accessed 24 May 2025.
138 Understanding the geology of Chilean volcanoes, https://www.unr.edu/nevada-today/news/2024/fres-grant-chilean-volcano, accessed 24 May 2025.
139 IFRC, Extreme fire-weather in Chile driven by climate change and El Niño, https://www.ifrc.org/article/extreme-fire-weather-chile-driven-climate-change-and-el-nino, accessed 24 May 2025.
140 C. Bravo, S. Cisternas, M. Viale, P. Paredes, D. Bozkurt and N. García-Lee, An unseasonal atmospheric river drives anomalous summer snow accumulation on glaciers of the subtropical Andes, *Cryosphere*, 2025, **19**, 1897–1913.
141 Honorable Cámara de Diputadas y Diputados, https://www.camara.cl/legislacion/ProyectosDeLey/tramitacion.aspx?prmID=15204&prmBOLETIN=14714-01, accessed 24 May 2025.
142 administrador, Tramitación del Proyecto de Ley Marco de Suelos en Chile, https://schcs.cl/tramitacion-del-proyecto-de-ley-marco-de-suelos-en-chile-esfuerzos-para-su-avance/, accessed 24 May 2025.
143 Gobierno de Chile, Chile avanza con litio, https://www.gob.cl/chileavanzaconlitio/, accessed 24 May 2025.
144 B. Montoya, Chile tiene un plan para impulsar la extracción de litio, ¿podrá hacerlo de forma sostenible?, https://dialogue.earth/es/negocios/chile-plan-impulsar-extraccion-litio-podra-hacerlo-de-forma-sustentable/, accessed 24 May 2025.
145 Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States, Young People's Potential, the Key to Africa's Sustainable Development, https://www.un.org/ohrlls/news/young-people%E2%80%99s-potential-key-africa%E2%80%99s-sustainable-development, accessed 25 May 2025.
146 N. Kasolene, *Africa Regional Review Meeting*, Malawi, 2021.
147 I. S. F. PE-GhIE, Africa's Green Mineral Wealth, https://www.speghana.com/post/africa-s-green-mineral-wealth-a-blessing-not-a-curse, accessed 25 May 2025.
148 C. C. Crawford Alec, Green Conflict Minerals, https://www.iisd.org/story/green-conflict-minerals, accessed 25 May 2025.
149 J. Boafo, J. Obodai, E. Stemn and P. N. Nkrumah, The race for critical minerals in Africa: A blessing or another resource curse?, *Resour. Policy*, 2024, **93**, 105046.
150 L. Leonard, Socio-environmental impacts of mineral mining and conflicts in Southern and West Africa: navigating reflexive governance for environmental justice, *Environ. Res. Lett.*, 2024, **19**, 104013.
151 African Union, About the African Union, https://au.int/en/overview, accessed 25 May 2025.
152 African Union, Africa's Green Minerals Strategy (AGMS), https://au.int/en/documents/20250318/africas-green-minerals-strategy-agms, accessed 25 May 2025.
153 Council of African Youth in Minerals, CAYM, https://caym.africa/, accessed 25 May 2025.
154 V. E. Akpan and D. O. Olukanni, Hazardous Waste Management: An African Overview, *Recycling*, 2020, **5**, 15.
155 A. Njoku, M. Agbalenyo, J. Laude, T. F. Ajibola, M. A. Attah and S. B. Sarko, Environmental Injustice and Electronic Waste in Ghana: Challenges and Recommendations, *Int. J. Environ. Res. Public Health*, 2023, **21**, 25.

156 A. Morrow, Global talks seek to curb e-waste dumping as Africa bears the brunt, https://www.rfi.fr/en/environment/20250430-global-talks-seek-to-curb-e-waste-dumping-as-africa-bears-the-brunt, accessed 25 May 2025.
157 Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal, https://enb.iisd.org/articles/basel-convention, accessed 25 May 2025.
158 Basel Convention - Home Page, https://www.basel.int/, accessed 25 May 2025.
159 AYACW, The African Youth Alliance for Chemicals and Waste, https://ayacw.org/, accessed 25 May 2025.
160 A. S. Huang and C. Y. H. Tan, Achieving Scientific Eminence Within Asia, *Science*, 2010, **329**, 1471–1472.
161 Indian National Science Academy and The Association of Academies and Societies of Sciences in Asia, *Science Policy Futures of Asia, INSA-Centre for Science & Technology Policy*, 2024.
162 G. Barrett and A. Homei, Decentring histories of science diplomacy: cases from Asia, *Br. J. Hist. Sci.*, 2024, **57**, 165–173.
163 A. Y. So and S. W. K. Chiu, Modern East Asia in World-Systems Analysis, *Sociol. Inq.*, 1996, **66**, 471–485.
164 P.-C. Lee and H.-N. Su, in *2015 Portland International Conference on Management of Engineering and Technology (PICMET)*, 2015, pp. 184–191.
165 A. Kennedy, Guiding science in China, *Science*, 2025, **387**, 1356–1358.
166 ASEAN, Going Beyond the Lab, https://asean.org/going-beyond-the-lab-asean-u-s-science-and-technology-fellowship-integrates-scientists-into-policymaking-2/, accessed 26 May 2025.
167 ASEAN Foundation, History and Mission, https://www.aseanfoundation.org/history_and_mission, accessed 26 May 2025.
168 ASEAN Foundation, The Fellows, https://aseanstfellowship.aseanfoundation.org/the-fellows/, accessed 26 May 2025.
169 ASEAN Foundation, ASEAN Science and Technology Fellowship, https://www.aseanfoundation.org/asean_science_and_technology_fellowship, accessed 26 May 2025.
170 Ministry of External Affairs and Department of Science and Technology, ASEAN India S&T Cooperation, https://aistic.gov.in/ASEAN/aistdfFellowship, accessed 26 May 2025.
171 N. Bolia, *ASEAN-India Cooperation through Technical Education Partnerships, Research and Information System for Developing Nations*, 2020.
172 ASEAN, ASEAN Science, Technology, and Innovation, https://asean.org/our-communities/economic-community/asean-science-technology-and-innovation/, accessed 26 May 2025.
173 International Science Council, Asia Science Mission, https://council.science/our-work/asia-science-mission/, accessed 26 May 2025.
174 *TOI Education*, The Times of India, 2024.
175 NITI Aayog, Home, https://niti.gov.in/, accessed 26 May 2025.
176 Britannica Editors, Oceania | Definition, Population, Maps, & Facts, https://www.britannica.com/place/Oceania-region-Pacific-Ocean, accessed 9 November 2025.
177 Australian Academy of Science, Early Career Urban Research Working Group – Strategy Update, https://www.futureearth.org.au/publications/early-career-urban-research-working-group-strategy-update, accessed 18 November 2025.
178 R. Elwalagedara, Green and Sustainable Chemistry Group Achieves Full Division Status, https://raci.org.au/blogs/panduka-jayasooriya/2024/09/17/green-and-sustainable-chemistry-group-achieves-ful, accessed 9 November 2025.
179 Royal Australian Chemical Institute, *RACI 2022 Mentoring Program*, University of New South Wales, 2022, https://www.science.unsw.edu.au/sites/default/files/documents/RACI%20Mentoring%20Progam%20Flyer,%202022%20.pdf, accessed 18 November 2025.
180 National Environment Protection Council, National Framework for Chemicals Environmental Management (NChEM), https://www.nepc.gov.au/projects/chemicals/nchem, accessed 9 November 2025.
181 Department of Climate Change, Energy, the Environment and Water, *National Plan of Action Global Framework on Chemicals*, Government of Australia, 2024.
182 Ministry for the Environment, Government of New Zealand, *Hazardous Substances and New Organisms Act 1996*, 1996.
183 New Zealand Ministry of Foreign Affairs and Trade, Chemical hazards and ozone protection, https://www.mfat.govt.nz/en/environment/chemical-hazards-and-ozone-protection, accessed 15 November 2025.
184 RRMA Global, New Zealand EPA Strengthens Reporting Rules for Hazardous Substance Importers and Manufacturers, https://rrma-global.org/news-details/new-zealand-epa-strengthens-reporting-rules-for-hazardous-substance-importers-and-manufacturers-/MjIwMw==, accessed 18 November 2025.
185 Centre for Green Chemical Science, Centre for Green Chemical Science, https://greenchemicalscience.blogs.auckland.ac.nz/, accessed 18 November 2025.
186 Centre for Green Chemical Science, Centre for Green Chemical Science, https://www.auckland.ac.nz/en/science/our-research/research-centres/centre-for-green-chemical-science.html, accessed 18 November 2025.
187 Environmental Investigation Agency, *Fact Sheet: Science Policy Interface*, SPREP.
188 IUCN, Oceania Nature-based Solutions guided by IUCN Global Standard, https://iucn.org/story/202405/oceania-nature-based-solutions-guided-iucn-global-standard-mr-singh-sheds-light, accessed 19 May 2025.
189 M. L. Vozzo, M. Christofidis, L. Griffiths, R. Kelly, M. L. Manion, S. Barmand, J. A. Bolin, P. A. Fuenzalida-Miralles, M. L. Harris, A. Issell, C. D. Kuempel, M. Martinez Diaz, M. Murunga, S. R. Palmer, N. Schaefer and J. Simpson, Advancing ocean sustainability through

better science integration: perspectives of Early Career Ocean Professionals, *Front. Ocean Sustain.*, 2024, **2**, 1526776.
190 SPREP, SPREP recognised as Oceania Regional Technical and Scientific Cooperation Support Centre for Global Biodiversity Framework | Pacific Environment, https://www.sprep.org/news/sprep-recognised-as-oceania-regional-technical-and-scientific-cooperation-support-centre-for-the-convention-for-biological-diversity, accessed 26 May 2025.
191 H. L. De Frond, E. van Sebille, J. M. Parnis, M. L. Diamond, N. Mallos, T. Kingsbury and C. M. Rochman, Estimating the Mass of Chemicals Associated with Ocean Plastic Pollution to Inform Mitigation Efforts, *Integr. Environ. Assess. Manage.*, 2019, **15**, 596–606.
192 P. Pereira, M. Inácio, D. Karnauskaitė, K. Bogdzevič, E. Gomes, M. Kalinauskas and D. Barcelo, in *Nature-Based Solutions for Flood Mitigation: Environmental and Socio-Economic Aspects*, ed. C. S. S. Ferreira, Z. Kalantari, T. Hartmann and P. Pereira, Springer International Publishing, Cham, 2022, pp. 79–137.
193 J. Staneva, N. Pinardi, G. Coppini, B. Jacob, W. Chen, P.-N. Jayson-Quashigah, J. Alessandri, L. Mentaschi and Y. Drillet, Advancing Marine Sustainability through Digital Twin What-If Scenarios in Nature Based Solutions, *Copernicus Meetings*, 2024.
194 E. Dobbelaar and J. Richter, An overview of young chemists' expectations towards the sustainable development of the chemical sector. Opinions that matter, *Pure Appl. Chem.*, 2022, **94**, 1–14.
195 Chemistry education must change to help the planet: here's how, *Nature*, 2022, **604**, 598, DOI: 10.1038/d41586-022-01109-z.
196 European Union, Science for Policy - Maximise your Policy Impact, https://academy.europa.eu/courses/science-for-policy-maximise-your-policy-impact, accessed 18 November 2025.
197 ACS, Sustainability and the Environment, https://www.acs.org/policy/publicpolicies/sustainability.html.
198 Department of Economic and Social Affairs, Transforming our world: the 2030 Agenda for Sustainable Development, https://sdgs.un.org/2030agenda, accessed 27 May 2025.
199 U. N. Environment, Global Environment Outlook – GEO-6, https://www.cambridge.org/core/books/global-environment-outlook-geo6-healthy-planet-healthy-people/8FE2F127F310561C679B620F1D2EDBA6, accessed 27 May 2025.
200 P. G. Mahaffy and J. Garcia-Martinez, From What Chemistry Can Do to What Chemists Should Do, *J. Chem. Educ.*, 2025, **102**, 4661–4665.