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Sustainability

Towards a Sustainable Future: Challenges and Opportunities for Early-Career Chemists

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Abstract: The concepts of sustainability and sustainable chemistry have attracted increasing attention in recent years, being of great importance to the younger generation. In this Viewpoint Article, we share how early-career chemists can contribute to the sustainable transformation of their discipline. We identify ways in which they can engage to catalyse action for change. This article does not attempt to answer questions about the most promising or pressing areas driving research and chemical innovation in the context of sustainability. Instead, we want to inspire and engage early-career chemists in pursuing sustainable actions by showcasing opportunities in education, outreach and policymaking, research culture and publishing, while highlighting existing challenges and the complexity of the topic. We want to empower early-career chemists by providing resources and ideas for engagement for a sustainable future globally. While the article focuses on students and early-career chemists, it provides insights to further stimulate the engagement of scientists from diverse backgrounds.

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Introduction

Sustainability is a concept which was defined by the United Nations (UN) in 1987 as "meeting the present needs without compromising the ability of future generations to meet their own needs".[1] Dating back to 2015, the UN unveiled the Agenda 2030 and its 17 Sustainable Development Goals (SDGs) as a call for action to guide concerted efforts across all nations in addressing major global challenges for the benefit of society and our planet towards sustainable development, leaving no one behind.[2] The SDGs are aimed at contributing towards fighting climate change, ending poverty, reducing inequalities and injustice, promoting health, protecting human rights and the planet, and ensuring prosperity for all.[3]

Although the SDGs' call for action is relatively recent, the implementation of sustainable practices in the chemistry context has been an ongoing endeavour for many years, and chemistry has a key role to play in addressing the SDGs by 2030.[4–6] When talking about sustainability in chemistry, one quickly thinks of the terms "green chemistry" and "sustainable chemistry", and it is important to understand the subtle differences between the two.[7] "Sustainable chemistry" has been termed to be a *sociohistorical framework* or concept which adapts to the ever-changing criteria of what makes something sustainable. Recent works provide an approach to operationalize the framework and achieve an actionable definition.[8] Generally, it encompasses all efforts along the value chain and life cycle that contribute to a shift towards sustainability and achieving the SDGs (e.g., chemicals sourcing, management, processing, production, product use, value/efficiency/performance, and disposal). "Green chemistry", in contrast, is a more well-defined term popularized by John C. Warner and Paul T. Anastas with the introduction of their twelve guiding principles to put theory into practice. It represents a *scientific framework* that directs chemists to design greener chemicals, processes, and products to meet economic profit goals with resource-saving and benign solutions towards a sustainable future.[9] In this regard, green chemistry provides a toolbox for chemists and represents the most important enabler of sustainable chemistry.[10]

A multi-stakeholder dialogue is essential to tackle all efforts in reaching the sustainability targets globally in a fair way. To achieve this, a joint collaborative effort and alignment between scientific societies, senior and junior leaders, industrial players, non-governmental organizations, policy-makers, and professionals in the decision-making process are required. In particular, chemists need to effectively communicate the importance of achieving the SDGs for the benefit of society and work on implementing them.[11–13] In the last few years, early-career chemists have raised their voices in this dialogue and advocated for change.[5,6,11,12,14–18] However, many may still be unaware of existing opportunities to engage and contribute. Additionally, some early-career chemists may be unsure about where to start and who to contact about opportunities for engagement, despite having an intrinsic motivation to contribute to sustainable actions.

As early-career chemists are aware of the consequences and implications of unsustainable practices happening today and their potential impact in the future, they know that their profession plays an important role in every aspect of our daily lives, including health, energy, nutrition, or clean water. They are also aware that they are the ones who will have to work on the necessary and economically feasible innovations in striving for a sustainable future.[5,6,19] Thus, there is a strong willingness among early-career chemists to contribute to solutions. In this regard, it appears that the opportunities to do so are impeded by barriers, many of which arise from unequal preconditions depending on their cultural, societal, regional, and economic backgrounds.

Although introducing these inequalities in detail would be relevant to better raise awareness of the diverse issues facing early-career chemists across the globe, we focus on selected barriers most relevant to early-career chemists. We present opportunities for early-career chemists, irrespectively of their background, to not only get involved and contribute to the advancement of the sustainable transformation of chemistry, but also to reduce inequalities that prevent the adequate support of researchers from historically marginalized communities and their contributions.

Discussion

To shed light on the challenges and opportunities for early-career chemists in contributing to sustainable development, we highlight relevant areas ranging from education, outreach, research and equity to science accessibility and publishing. While doing so, this article particularly focuses on early-career chemists. Both individual-level contributions, with immediate effect, and larger, longer-term measures (and more challenging issues) will be discussed. The term "early-career chemists" is used throughout this article. It broadly encompasses undergraduate and graduate students in the chemical sciences, as well as postgraduates in early-career stages, including postdoctoral researchers, research assistants, assistant professors, young professionals, and equivalent roles.

Educational System and Environment

A current challenge for early-career chemists is the lack of sustainable chemistry, green chemistry, and SDGs content and approaches in most educational systems despite their relevance for their future careers.[5–7,20] The subjective impressions of early-career chemists towards the relevance of sustainability in chemical education are highlighted in Figure 1, where the results of a survey conducted by the Young Chemists' Network of the German Chemical Society (GDCh-JCF), with support of the International Younger Chemists Network (IYCN) and the European Young Chemists' Network (EYCN), are depicted. Among the survey participants, over 90 % (463 out of 502 participants) would like sustainable chemistry to be addressed in more detail in studies and training ("much more" or "more" in

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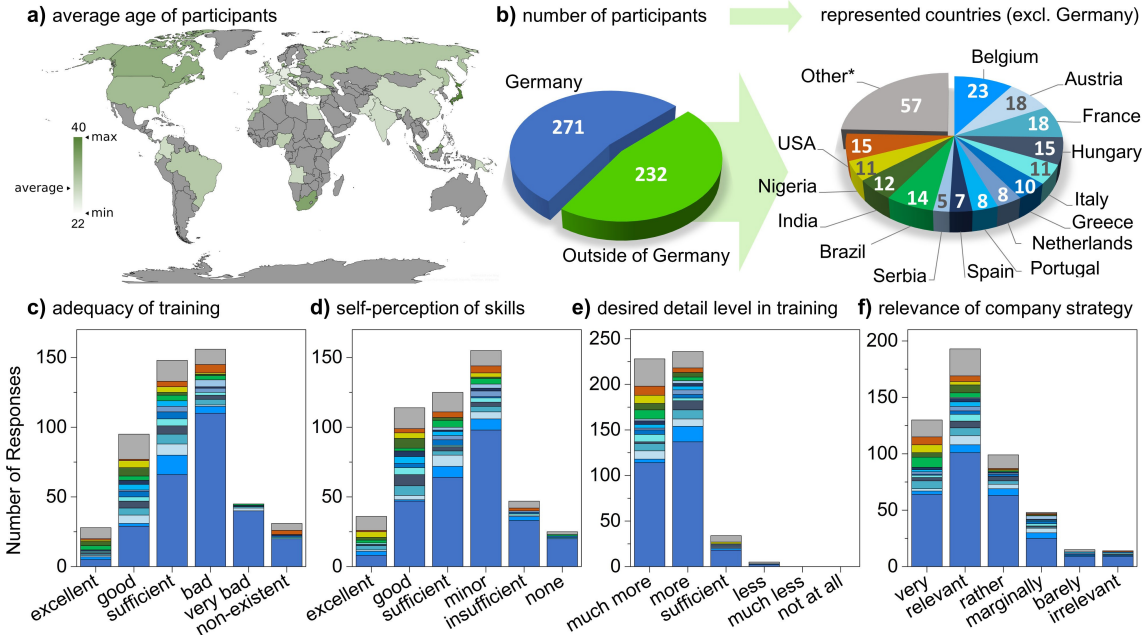

Figure 1. Results of an international survey pertaining to sustainability in chemical education conducted by the GDCh-JCF in 2020. The results are presented in more detail in the publicly available report of the survey.[21] **a)** and **b)** depict the demography of the participants, where **b)** relates to the responses to the question "In which country did you complete the majority of your higher education/training in the field of chemistry?". In **b)**, only countries with five or more respondents are explicitly named and European countries are depicted with a blue shade to highlight the overrepresentation of this world region in the survey results. **c)**–**f)** follow the colour scheme of **b)** for country representation and relate to responses to the following questions: **c)** "How would you describe the adequacy of your education on sustainable chemistry?" **d)** "Upon completion of your training, do you think that you will have the skills to contribute to the sustainability strategy of a company?" **e)** "Do you think that sustainable chemistry should be addressed in more detail in studies and training?" **f)** "Is the sustainability strategy of a company a relevant factor for you when choosing a career?". The results merely represent a snapshot of the subjective impressions and opinions of approximately 500 early-career chemists from 46 countries and may not be representative. *Responses from countries contained in "Other": Morocco (4), Pakistan (4), Romania (4), South Africa (4), United Kingdom (4), Canada (3), Ireland (3), Egypt (2), Malaysia (2), Poland (2), Russia (2), Slovakia (2), Switzerland (2), Turkey (2), Angola (1), China (1), Colombia (1), Costa Rica (1), Cyprus (1), Czechia (1), Denmark (1), Ecuador (1), Ethiopia (1), Gambia (1), Japan (1), Latvia (1), Mauritius (1), Nepal (1), Papua New Guinea (1), Philippines (1), Singapore (1). Data and Figures were adapted from the original survey results report, made available in the public domain. For more information and context, see survey data on Zenodo.[21]

Figure 1e), while most participants perceived the adequacy of their current training as "sufficient" or worse ("bad", "very bad", "non-existent") (380/502, 76 %, Figure 1c). Between 33 % (76/232 outside of Germany) and 56 % (151/270 within Germany) of early-career chemists perceive their skills for contributing to the sustainability strategy of a company as "minor" or lacking ("insufficient", "none") (Figure 1d). However, more than 80 % (425/502) state that the sustainability strategy of a company is a relevant decision factor for them when choosing a career (Figure 1f). These results call for significant improvements in chemical education to fulfil the needs of society. As the need and demand for responsible and sustainable practices in society increase, early-career chemists face inequitable access to education.[22,23] This is especially true in countries with poorer access to information. Despite the growing support of sustainable practices in all areas of life, (early-career) chemists have limited influence on driving a sustainable and green chemistry educational reform and avoiding misconceptions in teaching on the matter due to their underrepresentation among decision-makers.[12,24] A swift inclusion of green and sustainable chemistry content into chemistry curricula is crucial for a timely and systemic change, and early-career chemists are encouraged to engage in key roles to advance education for a healthier and more benign future.[4,25]

There are multiple barriers that contribute to inequitable access to sustainable and green chemistry education. Inequities are created by economic and social preconditions, political decision-making, and prejudice. They continue to persist for early-career chemists across educational and professional sectors. In particular, marginalized groups in science, technology, engineering, and mathematics (STEM) face systemic barriers and discrimination on the basis of their identities.[26,27] Despite increasing efforts, scholarships, and programs by institutions and associations to encourage and support marginalized groups in pursuing a STEM career (e.g., in the US, see funded STEM programs listed by the Institute for Broadening Participation IBP, see resources at the end of the article), the systemic discrimination remains ubiquitous, resulting in the loss of a diverse and talented set of early-career chemists in the workforce.

Encouragingly, equitable access to green and sustainable chemistry education and resources is being made possible by the work of international organizations such as Beyond Benign, My Green Lab, the American Chemical Society's

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Green Chemistry Institute (ACS GCI), the International Union of Pure and Applied Chemistry (IUPAC), or the Royal Society of Chemistry (RSC) (see resources). Various educational resources are created, disseminated, and provided by these organizations, thus allowing early-career chemists to learn more about the field. Additionally, joining such organizations enables further contributions to sustainable and green chemistry education through extensive networks. In this sense, the recently launched Green Chemistry Teaching and Learning Community (GCTLC) is an accessible alternative since it provides a platform for early-career chemists to further expand their networks, share resources, and connect with other members of the community to advance their green chemistry education journey (see resources). Some study programs are offered by institutions around the world, including the first university course in green chemistry at Carnegie Mellon University,[28] the field's first Green Chemistry Ph.D. program at the University of Massachusetts at Boston,[29] the Centre for Green Chemistry and a Master of Green Chemistry and Sustainable Technologies at Monash University in Australia,[30] study programs at the Institute of Sustainable Chemistry (INSC) of Leuphana University in Germany, and programs at the Green Chemistry Centre of Excellence at York University in the UK, among several others (see ACS GCI Green Chemistry Academic Programs and resources). Moreover, networks such as the Green and Sustainable Chemistry Network (GSCN) in Japan,[31] the Indian Green Chemistry Network Centre (GCNC), the Sustainable Chemistry Club of the International Sustainable Chemistry Collaborative Centre (ISC3) in Germany, and the IYCN and IUPAC's Global Conversation on Sustainability (GCS) highlight initiatives that facilitate the discussion about the pivotal role of education in enabling the sustainable transformation of chemistry among other objectives.[14,23] Finally, the attendance of dedicated green chemistry conferences, seminars, and summer schools, organized by organizations, including the RSC, ACS, Beyond Benign, the Gordon Research Conferences (GRC), IUPAC, or local Institutes such as the Green Sciences for Sustainable Development (GSSD) Foundation or the Institute of Sustainable Chemistry (INSC) of Leuphana University, can not only expand the network of interested early-career chemists but also contribute to valuable scientific exchanges, green chemistry education, mutual encouragement, and collaborations (also see resources).

When familiar with these opportunities, early-career chemists can practice and bring this knowledge to educational institutions by encouraging them to join discussions and educational programs, such as Beyond Benign's "Green Chemistry Commitment", which contributes to the increasing widespread adoption of green chemistry practices by chemistry departments across the globe.[32] On an individual level, teaching fellowships or assistantships at higher education institutions present valuable opportunities to include green and sustainable concepts, especially in practical courses or even reform chemistry curricula.

Beyond the invaluable efforts of well-established international organizations to provide their information equitably, many young chemists' networks around the world are working towards creating an equitable chemistry educational environment that aligns more broadly with the UN SDGs. Some examples of opportunities to contribute include young groups of national chemical societies, as highlighted by the initiative showcased in Figure 1, the Network of Early-Career Sustainable Scientists and Engineers (NESSE), and local groups at university campuses (see resources).

In summary, early-career chemists seeking to contribute to sustainable and green chemistry education can start by proactively seeking out available (online) resources and study in programs most accessible to them. To expand their scope and for more guidance, they can join various networks and organizations to find a community of like-minded individuals. Finally, they can leverage both knowledge and network resources to advocate for a stronger commitment to green and sustainable chemistry in education (e.g., through institutional committees). We acknowledge the fact that the ability to engage may differ depending on personal time constraints and barriers such as, but not limited to, financial means. Nonetheless, progress occurs when consistent, incremental efforts are made towards a common goal, and we encourage all early-career chemists to consider that even the smallest efforts can have a great impact.

Outreach to Society and Policymakers

As a simple but possibly effective measure to perform outreach with little effort, we want to encourage early-career chemists to promote and share important works contributing to the attainment of the SDGs and drive the discussion in the communities they engage with. For those more eager to reach a broader audience and to participate in outreach activities and sustainable development discussions with the public and policymakers, further opportunities exist. Although there are myriads of ways to approach outreach, in this article, we specifically highlight and advocate for the active participation of early-career chemists in national or international organizations, chemical societies, and their respective early-career platforms. Such engagement is easier to start due to existing structures and projects, and it is rewarding and paramount to accelerate the demand for sustainability by the chemistry community. By being involved in a reputable organization, one can credibly and effectively communicate challenges, opportunities, and needs to the chemistry community, as well as to the public.[11] In addition, chemists can increase their professional network, gain invaluable new insights and different perspectives about the bigger picture, and learn important transferable skills that contribute to personal and professional growth. Further benefits were recently highlighted for the partnership between the IYCN and IUPAC.[11]

Early-career chemists with initiative and willingness to access the wealth of institutions that are looking for contributors with a scientific background will find opportunities both on a voluntary basis and as employees. The reputation of organizations should not be intimidating to early-career chemists,[33] as the early-career or youth plat-

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forms associated with large international organizations such as IUPAC, the UN Educational, Scientific and Cultural Organization (UNESCO),[34] or the UN Environment Program (UNEP) have low entry barriers for committed young people (see resources). As an example, the IYCN connects early-career chemists from around the world and runs several projects that contribute to sustainability outreach, such as an experiment competition,[15,17,18] webinars,[35] symposia at conferences,[11] and an annual event devoted to sustainability with local activities around the world – the GCS.[14]

Organizations such as IUPAC, the IYCN, NESSE, the Global Young Academy (GYA) and the Major Group for Children and Youth to UNEP (UNEP-MGCY), among others, provide a platform for early-career chemists to communicate their concerns and suggestions to policymakers and relevant stakeholders (see resources). The science-policy interface is complex and requires an understanding and training of scientists in how to communicate effectively with decision-makers in the policymaking environment – something that these organizations and others can assist with.[12] Beyond this, it is noteworthy that there are also programs that aim to increase the number of scientists in policy positions and opportunities to volunteer on expert committees that allow early-career chemists to directly work on policies where they can contribute to the implementation of sustainable and green chemistry reforms, such as the American Association for the Advancement of Science (AAAS) Policy Fellowships, the GYA, the National Science Policy Network (NSPN), or The World Academy of Sciences (TWAS) (see resources).

In conclusion, larger organizations and networks can not only establish awareness and connections, but also provide relevant training and mentorship to early-career chemists to pursue activities towards sustainable development.[36] The barriers to getting involved in policymaking are diverse, while chemical societies, early-career networks, and young academies can facilitate engagement and support such involvement. Most organizations are open to the idea of including junior voices in their discussion. Recent examples include the creation of the Institute of Chemistry of Ireland Young Chemists Network (ICI-YCN) in 2021 and the Thailand Younger Chemists Network (TYCN), endorsed by the Chemical Society of Thailand (CST), in 2023 (see resources). Both, proactive early-career chemists, and supportive senior chemists, can catalyse the establishment of new opportunities for engagement. In addition, international networks and organizations can provide guidance, collaboration and support for individuals who want to pursue new projects. We encourage early-career chemists to start today and think big, develop creative ideas or projects, and seek out platforms, organizations, and networks that can help make their goals achievable.

Research Environment and Culture

Green and sustainable chemistry research is rapidly gaining interest and is becoming attractive due to the wealth of opportunities it has to offer. The number of yearly articles published related to green and sustainable chemistry is increasing substantially (Figure 2), and (early-career) chemists should use this momentum and current interest to grasp the many opportunities to find sustainable alternatives for conventional (chemical) solutions. Major funding agencies, including the National Science Foundation in the US (NSF), the German Research Foundation (DFG), and the EU research and innovation framework programme Horizon Europe, are already considering such aspects in their research grants to help raise awareness on the importance of green and sustainable chemistry research (see resources). In this context, funding bodies may consider implementing robust mechanisms to avoid "greenwashing" and ensure meaningful allocations of funds. Strong funding support is important for both fundamental and applied research. In fact, increasing public interest and new policy regulations have fuelled ever greater public and commercial funding and created many job opportunities as skills in these disciplines are in high demand. Moreover, many initiatives from well-known foundations and private businesses have been launched to motivate early-career chemists to work on green chemistry projects, such as the "Elsevier Foundation Chemistry for Climate Action Challenge", or the "Green Chemistry for Life research grants for young scientists" issued by PhosAgro, UNESCO, and IUPAC. This makes a career choice for sustainability even more attractive for early-career chemists.

When choosing a research topic or direction aligned with the values of green and sustainable chemistry and the UN SDGs, support from research advisors and professional organizations can be valuable. While we do not discuss the developments in research here, we highlight the surrounding research environment and culture. Chemistry students and researchers, early on in their careers, specialize and choose their research field.[13,37] In this regard, they can actively consider the underlying principles of green chemistry from

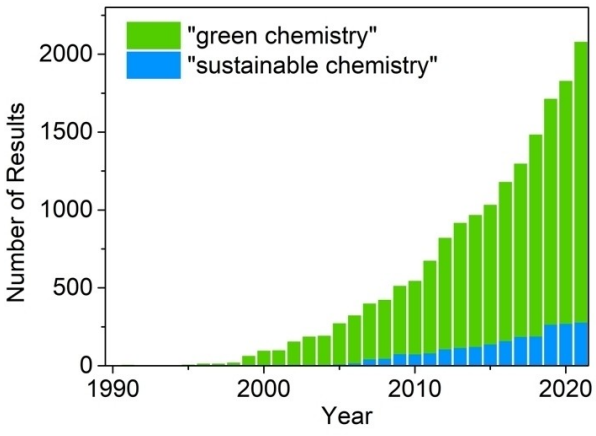

Figure 2. Number of results for a search query in Web of Science™ for the adjacent keywords "Sustainable Chemistry" or "Green Chemistry" in title, abstract or topic for the years 1990–2021. The exact query is given at the end of the document. The trend matches that observed for Latin America in a recent review article.[40]

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the outset in any area of chemistry, as long as they maintain a sustainability mindset, exercise critical thinking, and keep the bigger picture around their research in mind while avoiding "greenwashing".[38,39] They may either choose a research topic with a clear goal towards sustainable solutions (e.g., batteries) or one that seems less directed towards sustainability (e.g., drug design) but deploy new and greener methodologies to improve, for example, processes and practices. Highlighting successes of either of the approaches at conferences, in application notes and in scientific articles can contribute to a broader implementation for the benefit of society.

Although the intrinsic motivation of chemists is paramount, the external environment may heavily influence the success of their innovative approaches and proposed changes to established practices. Chemists may face significant challenges when confronted with community members trying to discredit modern and greener approaches, especially when they have conservative beliefs while occupying positions of power. This could include supervisors, graduate committee members, teachers or well-known colleagues.[41] While the opinions of such peers can be valuable to dispute a topic, it is important to identify and build resilience against outdated arguments and false claims to advance a cultural shift in research and enable a transformation towards developing more sustainable and greener solutions.

As experts on a research topic, early-career scientists should base their unbiased decisions on state-of-the-art research and information, and judge how feasible sustainable solutions are. In this context, it should also be noted that the choice of a supportive research group and an open-minded supervisor are imperative to drive change.[36,42] However, if the environment is not as supportive as anticipated, early-career chemists can find role models to serve as informal mentors, committee members, or co-supervisors to navigate difficult situations. Such role models and supportive interactions may be found at conferences, in student groups, or through professional networks and mentoring programs. Although the research environment is becoming increasingly supportive of sustainable innovations, it is not yet equally supportive to all, as will be elaborated on in the following section.

A Mindset to Support Chemistry for Equity

Research towards sustainable practices in chemistry may contribute to overcoming challenges and inequalities in different regions of the world. We aim to briefly highlight how innovation for sustainability in chemistry can significantly advance equity, diversity, and inclusion. Looking at the central challenges of our time, the transformation of chemistry is at the forefront of solutions in almost all areas. This includes many current inequalities arising from the way we practice chemistry and manage waste. Thus, when talking about sustainability, it is important to also emphasize the diversity and equity perspectives. Regional disparities exist throughout the supply chain and persist beyond the lifetime of a chemical or product. Thus, chemical innovation and development for sustainability can contribute to equity in different ways and, at the same time, support the implementation of bio- and circular economy and sustainable resource management:[43] 1) By uncovering new ways to reduce fossil-dependency and its resulting power-dynamics,[44] 2) by creating better solutions to reduce waste and chemical mismanagement hazards that disproportionately affect historically marginalized groups,[9] 3) by contributing to the development of agriculture and food supply to support world nutrition,[4] and 4) by considering the diversity of people and the environment in the development of biologically active chemicals, supplements and pharmaceuticals, or products which may also release biologically active components during their use or upon degradation for the benefit of human health.[45] Each of these goals and others require intense research and early-career chemists can significantly contribute to pursuing those.

When practicing research, it is important to consider that a supportive environment at the institutional level is crucial to achieve the best results. By approaching science and education with ethical values of equity, diversity, inclusion, and respect, and understanding it as a collaborative effort rather than a competition, everyone can help to create a more supportive work environment and attitude towards research. Such an approach will benefit the profession, those directly involved, and, ultimately, society.[27,46] A valuable action that anyone can take is to encourage fellow students and colleagues from historically marginalized communities to pursue or continue a career in STEM. Early-career chemists can further strengthen this encouragement by continuing to support and stand up for rising champions and role models from these groups to overcome any persisting marginalization in the workplace. Reflecting on diversity and work culture supports the creation of equal opportunities and the inclusion of more perspectives required for a socially fair sustainable transformation. Finally, the establishment of collaborations with researchers from under-represented groups, institutions, and regions can be mutually beneficial to increase the research impact and break down various access and visibility barriers and should, thus, be considered more often also by early-career chemists.[47]

In summary, working towards a mindset to support chemistry for equity means "reflection and adjusted action," both in research goals and interpersonal behaviour. There is a low entry barrier for early-career chemists to start working and improving on this today, even on a rather individual level. For those that would like to advocate for this more strongly, outreach opportunities exist to contribute to initiatives and reports put forward by organizations such as ACS, GDCh, RSC, Diversify Chemistry, the Open Chemistry Collaborative in Diversity and Equity (OXIDE), 500 Queer Scientists, the Organization for Women in Science for the Developing World (OWSD), LatinXChem, or BlackInChem (see resources).[48]

Accessibility and Scientific Publishing

Access to science globally depends on political, economic, and social factors, resulting in often systemically limited educational opportunities and fluctuating research funds for many chemists.[49] Limited time for an extensive education, practicing research, or engaging in activities for sustainability creates an

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additional barrier for community members if they need to secure basic needs already at a young age. This may lead to situations where the ones most affected are not involved in addressing the challenges, leading to an underrepresentation of important views from those demographics.[50] To address this, policymakers, funding agencies, and organizations may provide programs and funding especially targeted at early-career chemists, with an emphasis on historically marginalized communities. Moreover, the chemistry community at large can first and foremost contribute to this endeavour by raising awareness of the issue and amplifying the voice of those communities through adequate citation and research practices. As policymakers and funding organizations play an important role in shaping the research incentives in any area, they may specifically support regions or topics. Early-career chemists can help focus attention on current issues by communicating them at conferences and through their network. By doing so, the message may better reach relevant stakeholders, directly or indirectly, which can assist in creating new programs and in providing resources to reduce some of the barriers.

Another major barrier is the access to free reading and sharing of research data. Research is typically disseminated in the form of publications by publishers whose business model is either to publish articles at no cost to authors behind a subscription pay-wall to readers, or authors pay an article processing charge (APC) for having the article open access to the public. The high publication (pay-to-publish) and subscription (pay-to-read) fees to share and access research articles, respectively, prevent the inclusion of all chemists to the dissemination of scientific research data and information, including those focused on sustainability.[51] Although several publishers offer fee waivers to publish open access or free access to otherwise pay-walled articles to developing nations, this does not cover many smaller institutions and research groups in richer countries. The younger generation should strive for improving global research access by using open access publishing strategies and following FAIR data management principles (Findability, Accessibility, Interoperability, Reuse) that allow for better transparency and more effective collaboration towards sustainable solutions.[52]

Open access publishing strategies include: 1) publishing a preprint on a dedicated server prior to journal publication, 2) self-archiving an unedited accepted version of the article (green open access), or 3) publishing open access with a journal that offers this service (gold open access). For the latter, several publishers already negotiated agreements with institutions where libraries pay bulk fees to allow open access publishing for authors at no direct cost to them (see resources). However, this model leaves out researchers from institutions and disciplines less well-funded to pay for such agreements. The shift from pay-to-read to pay-to-publish models has the potential to leave out diverse sets of authors in lower income countries from publishing in these journals, posing an equity issue.[53,54] Although chemists may in some cases receive discounts by reviewing for journals, this does not help to fully overcome funding barriers, as it still puts researchers with systemically limited access to funds in a disadvantageous position. International networks such as the Global Sustainability Coalition for Open Science Services (SCOSS) are working to provide a cost-sharing framework (see resources). Diamond open access, available, for instance, by the journals *ACS Central Science* or the RSC's *Chemical Science* offer free open access, paid for by the publisher. Such a model, paid for by funders, could be a vital solution.[53,54] Already since the 1990s, databases such as the scientific electronic library online (SciELO) have paved the way to make open access articles findable and accessible to all.[55] The UNESCO-supported directory of open access scholarly resources (ROAD) – which combines indexing and abstracting databases, such as the directory of open access journals (DOAJ) – and its complementary platform, the global open access portal (GOAP), are further, more recent examples of global efforts to provide and encourage open access resources worldwide and support authors in the workflow of open access publishing (see resources).[56] Generally, the support and implementation of universal good practices for accessible research and data by the current generation of scientists, including early-career chemists, is crucial to accelerate and validate research towards sustainable solutions that are needed as soon as possible to reach global sustainability goals. Sharing and finding research freely is essential for equitable practices globally. Supporting efforts to create equal access opportunities and a more diverse scientific discourse is a major collective task, and the success of individual contributions may be difficult to grasp. However, even small considerations in scientific practices can pave the way and help improve the *status quo*. To contribute, early-career chemists should advocate for open-access publishing when they can and support diverse perspectives and relevant works by paying attention to literature research and citation practices for a socially fair, sustainable transformation. Especially, when publishing works that claim sustainability benefits, a citation list should contain a diverse set of relevant perspectives to credibly unify the different aspects of how unsustainable practices affect different communities. Young researchers who are questioning unsustainable practices and striving for sustainable change are beneficiaries while they are working to become more established in their field and attract more funds for the inclusion of important, underrepresented perspectives.

Summary and Conclusions

There are many opportunities for early-career chemists to influence and shape the way we practice chemistry and contribute to a more sustainable future. With initiative and commitment, individual actions and engagement through organizations represent the easiest yet effective contribution pathways (Scheme 1). Although there are different challenges and barriers for the diversity of people, education systems and regions, we believe to have highlighted some of the challenges and opportunities. Early-career chemists can and should contribute through self-education, teaching, and reflection on the principles of green and sustainable chemistry in their research. It is important that active researchers contribute to more sustainable solutions through innovation and making their findings accessible to all. In addition, depending on the workload and available time among other responsibilities, early-career chemists can contribute through outreach, making use of engagement opportunities, and by raising awareness of the need for

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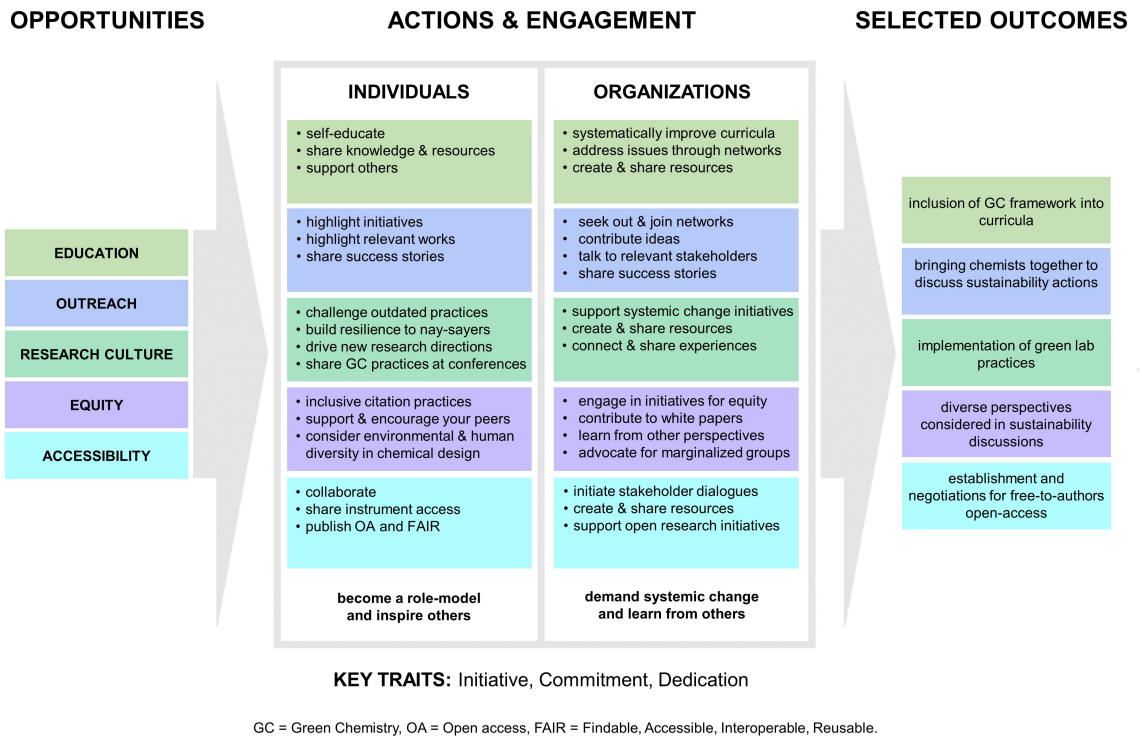

Scheme 1. Simplified Scheme of how early-career chemists can contribute to sustainable change. Individual and joint actions through dedicated organizations are highlighted as they provide good opportunities to contribute. The scheme shows that, with initiative, commitment, and dedication, simple actions can account for significant contributions in various areas.

sustainability in the curriculum at their institution or alma mater. Finally, every early-career chemist can contribute by encouraging, supporting, and advocating for the inclusion of historically marginalized communities and by creating a mindset to undoubtedly supporting sustainability and equity. This especially holds true for citation practices when publishing works on sustainable transformation that affects global communities and requires the inclusion of diverse perspectives. As a final piece of advice, the authors would like to note that, in practice, resilience and commitment are most important in almost every aspect. When ambitious visions and ideas are questioned, early-career chemists should reflect on the facts and take care to avoid being persuaded by power dynamics in a dispute. However, it is important to trust in ideas, to reflect on what is important, and to find a way to turn it into reality. By doing so, we, as early-career chemists, have the potential to become champions of sustainability and, eventually, inspire others to do the same for the benefit of society.

Notes

The organizations and opportunities mentioned here are a selection of initiatives that exist around the world. We would like to acknowledge that we highlight those opportunities known to us and that we greatly encourage early-career chemists to seek out change-making communities and organizations that are most easily accessible to them. We are aware that the complexity of the topic leaves room for a more extensive examination of the aspects that contribute to each of the sections and that we did not cover every detail, especially regional and societal disparities, despite our best efforts. However, we have attempted to summarize the most important key messages for young and early-career scientists to be actively involved and engaged in sustainability.

The search queries for "Web of Science™" (Core Collection) used on April 30th 2023 for obtaining the data plotted in Figure 2 were as follows: **1)** (TS = ("Green Chemistry") OR TI = ("Green Chemistry") OR AB = ("Green Chemistry")) **2)** (TS = ("Sustainable Chemistry") OR TI = ("Sustainable Chemistry") OR AB = ("Sustainable Chemistry")). TS = Topic, TI = Title, AB = Abstract.

Resources and Abbreviations

An overview of resources and programs highlighted in the Viewpoint Article is provided in this section (see Table 1). The resource list is non-exhaustive and merely gives an overview of some examples referenced in this article. We would like to note that there are many newly formed institutions that support green and sustainable chemistry practices. Moreover, note that we provide general links to the resources to avoid expiry of links to more specialized programs and activities in the future.

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Additional Abbreviations

APC Article Processing Charge
FAIR Findable, Accessible, Interoperable, Reusable
GC Green Chemistry
OA Open Access
SDG Sustainable Development Goal
STEM Science, Technology, Engineering, and Mathematics

Table 1: Overview of resources and programs highlighted in the Viewpoint Article.

Resource	Link
AAAS (American Association for the Advancement of Science) Policy Fellowships	https://www.aaas.org/fellowships
ACS (American Chemical Society) (e.g. Green Chemistry Institute – GCI, Green Chemistry Academic Programs, Student Chapters, Awards [Green Chemistry Student Chapter Award], Grants [Early Career Postdoctoral-Faculty Bridge Grant from ACS GCI], Scholars Program)	https://www.acs.org
BlackInChem	https://twitter.com/blackinchem
Beyond Benign	https://www.beyondbenign.org
CST (Chemical Society of Thailand)	https://www.chemsocthai.org
TYCN (Thailand Young Chemists Network)	
DFG (German Research Foundation)	https://www.dfg.de
Diversify Chemistry	https://diversifychemistry.com
DOAJ (Directory of Open Access Journals)	https://doaj.org/
Elsevier Foundation	https://elsevierfoundation.org
EU funding, including Horizon Europe	https://research-and-innovation.ec.europa.eu/funding en
EYCN (European Young Chemists' Network)	https://www.eycn.eu
GCNC (Indian Green Chemistry Network Centre)	https://www.gcnc.in
GCS (Global Conversation on Sustainability)	https://www.gcs-day.org
GCTLC (Green Chemistry Teaching and Learning Community)	https://gctlc.org
GDCh (German Chemical Society) (e.g. Sustainable Chemistry Division, Sustainability Team of the Young Chemists Network (JCF), Awards, e.g. PhD Award for sustainable chemistry)	https://en.gdch.de https://jcf.io
GOAP (Global Open Access Portal)	https://goap.info/
GRC (Gordon Research Conferences)	https://www.grc.org/
GSSD (Green Sciences for Sustainable Development) Foundation	https://www.gssd-foundation.org/
GYA (Global Young Academy)	https://globalyoungacademy.net
IBP (Institute for Broadening Participation) list of funded STEM programs	https://www.pathwaystoscience.org/
ICI YCN (Institute of Chemistry of Ireland Young Chemists Network)	https://www.chemistryireland.org/young-chemists-network
INSC (Institute of Sustainable Chemistry) of Leuphana University	https://www.leuphana.de/en/institutes/insc.html
ISC3 (International Sustainable Chemistry Collaborative Centre)	https://www.isc3.org
IUPAC (International Union of Pure and Applied Chemistry)	https://iupac.org
IYCN (International Younger Chemists Network)	https://www.iycnglobal.com
LatinXChem	https://www.latinxchem.org
Monash University	https://www.monash.edu
My Green Lab	https://www.mygreenlab.org
NESSE (Network of Early-Career Sustainable Scientists and Engineers)	https://www.sustainablescientists.org/
NSF (National Science Foundation)	https://new.nsf.gov
NSPN (National Science Policy Network)	https://www.scipolnetwork.org
OWSD (Organization for Women in Science for the Developing World)	https://owsd.net
OXIDE (Open Chemistry Collaborative in Diversity and Equity)	http://oxide.jhu.edu
Projekt DEAL	https://deal-konsortium.de/en
ROAD (Directory of Open Access Scholarly Resources)	https://road.issn.org/
RSC (Royal Society of Chemistry)	https://www.rsc.org
SciELO (Scientific Electronic Library Online)	https://scielo.org/
SCOSS (Global Sustainability Coalition for Open Science Services)	https://scoss.org
TWAS (The World Academy of Sciences)	https://twas.org
UNESCO Green Chemistry for Life research grants	https://www.unesco.org/en/basic-sciences/green-chemistry
UNEP (United Nations Environment Program) MGCY (Major Group for Children and Youth) (e.g. Chemicals & Waste Youth Platform)	https://www.unmgcy.org https://www.youthenvironment.org
UNESCO (UN Educational, Scientific and Cultural Organization)	https://www.unesco.org/en
York University	https://www.york.ac.uk
500 Queer Scientists	https://500queerscientists.com

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Author Contributions

E.D., S.S.G., J.B., and T.J., conceived the project. E.D. led the project. All authors contributed representative essays on challenges and opportunities in the world regions they are most familiar with. E.D. summarized the essays, defined the themes of the paragraphs, and wrote the first manuscript draft with the support of S.S.G., J.L.V., N.K.O., J.B., and T.J.. E.D., J.B., and T.J. coordinated project alignment. All authors contributed to the writing of the final version of the manuscript through extensive review.

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Conflict of Interest

S.G., Y.S.L.C., H.I., H.L.L., V.N., R.A.B. and M.R. have been involved in committees of the IYCN, while E.D., B.M.B.F., A.N. and N.A.O. have been board members of the IYCN, and J.B., T.J. and B.L.D. have been Chairs of the IYCN. J.L.V. and N.O. are affiliated with Beyond Benign. E.D. was Chair of the GDCh-JCF and led its sustainability team, as well as the survey mentioned in Figure 1. E.D. is a member of the sustainability committee of GDCh. T.J. was a board member of the GDCh-JCF and the EYCN, and J.B. has been a team member of the EYCN. E.D., Y.S.L.C., H.I., V.N., R.A.B., and T.J. are Task Group members, and J.B. and J.L.V. are Task Group co-chairs of the GCS project by IUPAC and the IYCN. T.J. is an Advisory Board Member of ISC3 and has been a Researcher at Monash University. J.B. is a member of the Global Young Academy. E.D. is a founding member and advisor to the Coordination Committee of the Chemical's & Waste Youth Platform of UNEP MGCY and has worked together with ISC3 in volunteer activities including a survey on young chemist's opinions on the sustainable transformation of the chemical sector. J.L.V. is a coordination team member of the Chemicals & Waste Youth Platform of UNEP MGCY and was part of the Network of Early-Career Sustainable Scientists and Engineers (NESSE). H.I. is co-founder and advisor to the ACS international student chapter at Alexandria University in Egypt, H.L.L. is founding member of the ACS International Malaysia Chapter, and A.N. was President of the ACS Students' Chapter AMU, India.

Data Availability Statement

The data that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.10401951, reference number 10401952.

Keywords: sustainable chemistry · green chemistry · early-career chemists · education · sustainability

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