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A promise to a sustainable future: 10 years of the Green Chemistry Commitment at Beyond Benign

Amy S. Cannon, *[a] John C. Warner,[a,b] Juliana L. Vidal, [a] Natalie J. O'Neil, [a] Monica M. S. Nyansa, [a] Nimrat K. Obhi[a] and Jonathon W. Moir [a]

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Green chemistry education is a fundamental tool for the achievement of a sustainable future at the molecular level. It allows the development of a scientific workforce and knowledgeable citizenry with the skills to choose, assess, and further design more benign processes for human health and the environment. In 2007, Dr Amy Cannon and Dr John Warner co-founded a non-profit organization known as Beyond Benign to empower educators dedicated to creating a systemic, long-lasting, and meaningful change in education through green chemistry. The Green Chemistry Commitment (GCC) was launched in 2013 with 13 participating institutions as Beyond Benign's higher education program to support universities, colleges, schools, and centers worldwide to incorporate green chemistry in their curricula. The Commitment is a signal of intent provided by higher institutions to begin, continue, or optimize their unique green chemistry journeys, thus preparing the future workforce to address our societal and environmental challenges. Over 150 institutions in more than 15 countries are now part of this growing program, with the ultimate goal of advocating for a diverse, accessible, inspiring, and empowered green chemistry community capable of providing the transformation needed for a sustainable future.

Introduction

Green chemistry is a science developed in the 1990s as a mechanism for chemists to play a role in the environmental and sustainability movement. Well-defined by 12 foundational principles, green chemistry provides a holistic framework for which chemists can find opportunities to reduce hazards and impacts within the design stage of a product life cycle.[1] As a science, green chemistry is a means for accomplishing many global initiatives to reduce waste, increase efficiencies and minimize harm through intentional, thoughtful molecular design. As a movement, green chemistry compels chemists to understand the impacts of the practice of their trade and empowers them to act toward a more sustainable planet. The 12 principles of green chemistry enable chemists to take a lead role in creating a sustainable foundation for which materials scientists, engineers, and additional professionals can utilize and implement more sustainable technologies.

Early in its adoption, chemistry educators recognized the tremendous opportunity that green chemistry provides to reduce laboratory hazards, increase reaction and energy efficiencies, and reduce laboratory waste within an academic setting. However, since educators were traditionally not trained (and currently are not still) on green chemistry topics, there was a lack of green chemistry resources and support available to those looking to practice the 12 principles in their teaching, research, and service. This led to the development of numerous greener educational resource collections,[1–3] journals dedicated to the growing field,[4,5] and support for the field through awards programs,[6–9] professional development workshops,[10] and dedicated networks.[11–16] Green chemistry activities have been growing worldwide,[17,18] with numerous approaches towards adopting green chemistry in teaching, research, service, and beyond. While this is not meant to be a comprehensive history of the development of the field, we point the reader to other robust summaries. The growing number of activities and resources worldwide focused on green chemistry were indicative of the growing demand for community support to implement green chemistry into the education systems. To address this demand and foster this growing green chemistry community, Dr Amy Cannon and Dr John Warner founded Beyond Benign in 2007.

Beyond Benign

Beyond Benign is a 501 (c)3 non-profit organization that was founded to provide support to educators and institutions looking to adopt green chemistry in their teaching and prac-

[a]*Beyond Benign Inc., 18 Church Street, P.O. Box 1016, Wilmington, MA, 01887, USA. E-mail: amy_cannon@beyondbenign.org*
[b]*The Technology Greenhouse, 100 TradeCenter, Woburn, MA, 01801, USA*

tice. The organization has a strong foundation in both K-12 and higher education professional development,[19] outreach,[20] and curriculum development,[21] addressing resource and support needs for chemistry educators. Beyond Benign envisions a world where the chemical building blocks of products used daily are healthy and safe for all. To do so, its mission is to foster a green chemistry community that empowers educators to transform chemistry education for a sustainable future. The organization aims to find effective means for supporting educators to bring green chemistry to their research, teaching, and service. Throughout the years, Beyond Benign's work has transitioned from addressing resource gaps to supporting and growing a green chemistry community of practice.[22,23] The organization has carried this out through its flagship programs for supporting educators and institutions in both K-12 and higher education: the K-12 Lead Teacher Program,[24] and the higher education-focused Green Chemistry Commitment program. This manuscript will share the progress of the Green Chemistry Commitment through 10 years of growth.

The Green Chemistry Commitment

The Green Chemistry Commitment (GCC) is a non-prescriptive program created by Beyond Benign with the help of a dozen practitioners from the community to catalyze a worldwide systemic and lasting change in higher education through green chemistry, thus reflecting the mindset shift in industries, individuals, and organizations regarding achieving a sustainable future.[25,26] The idea of creating a program dedicated to achieving sustainability through education was based on other voluntary and non-regulatory approaches to promote lasting change in our society. One important example is the 'The Presidents' Climate Leadership Commitments' organized by Second Nature, taken by higher institutions to reduce greenhouse gas emissions and achieve carbon neutrality.[27] The GCC was inspired by this and similar proactive approaches, using a distinct strategy focused on expanding and amplifying the diverse efforts of leaders in the field.[26]

The GCC works to empower institutions in solving our societal and environmental challenges by supporting their unique and diverse education transformation journeys through green chemistry.[25,26] To provide a flexible and realistic framework for guiding change in academia, the GCC was shaped by a faculty advisory board with members from higher education institutions, as well as green chemistry professionals representing business, government, and non-profits globally. To shape the GCC program while facilitating and tracking the adoption of green chemistry by higher education institutions, the faculty advisory board designed a framework of four student learning objectives. Upon joining the GCC, participating institutions (*i.e.*, GCC signers) commit to continual improvement in green chemistry implementation, thus working on incorporating the following four student learning objectives throughout their chemistry journeys, using their own approaches, resources, and timelines:

(i) Theory: Students should have a working knowledge of the 12 principles of green chemistry. The 12 principles of green chemistry, developed by Dr John Warner and Dr Paul Anastas (published in 1998), represent a holistic framework for designing processes and products with less negative impact on human health and the environment.[1] By using the 12 principles of green chemistry, students can correlate this interlinked system of guidelines to reduce and eliminate hazards.

(ii) Laboratory skills: students should have the ability to assess chemical products and processes, and design greener alternatives when appropriate. Students with practical green chemistry skills understand the power of 'smart' molecular design, thus being able to strategize unique and sustainable approaches to create our society's molecular building blocks.

(iii) Toxicology: students should have an understanding of the basic principles of toxicology, the molecular mechanisms of how chemicals affect human health and the environment, and the resources to identify and assess molecular hazards. As molecular designers, chemistry students should understand how chemical structures and properties influence toxicity and environmental impact, so they are able to develop greener and safer chemical products and processes.

(iv) Application: students should be prepared to serve society in their professional capacity as scientists and professionals through the articulation, evaluation, and employment of methods and chemicals that have less negative impacts on human health and the environment. The green chemistry knowledge acquired by students throughout their degree programs can be applied beyond the laboratory, as they can work towards the betterment of the global community as citizens with responsible principles and practices.

While every GCC signer agrees on these student learning objectives, each institution incorporates these objectives into its chemistry curriculum at the undergraduate, graduate, and postgraduate levels with approaches that best serve its community. The Commitment is a mechanism to share these unique approaches as an inspiration, a starting point, and a work to be built upon to advance green chemistry globally.

10 years of the Green Chemistry Commitment

Building a community of practice

The GCC program was launched in 2013 during the 17th Annual Green Chemistry & Engineering Conference in Washington, DC. At this event, 13 U.S.-based higher education institutions (*i.e.*, GCC founding signers) committed to giving students the required skills and knowledge to solve our global challenges. Three years after its launch, the University of Toronto (Canada) joined the GCC program as its first international signer. The number of participating institutions outside of the U.S. has continued to increase ever since. 5 years later, the Commitment community was then brought together again for the first GCC Summit, held at the Biennial

Conference on Chemical Education (BCCE) in 2018. During this event, Beyond Benign, faculty and students from current and prospective GCC signing institutions joined a full-day discussion of implementing green chemistry in academia and exploring partnerships to address resource gaps. The agenda included dialogues around integrating toxicology into chemistry courses, green chemistry courses and programs, green chemistry integration into undergraduate teaching labs, green chemistry undergraduate research, as well as green chemistry outreach. The GCC Summit is now an annual event organized by Beyond Benign to unite the community and support the integration of green chemistry into education. The Summit was hosted in-person in 2019 and then online during 2020–2022. The 10-year celebration of the Commitment program was hosted at the GCC Summit in 2023 during the 27th Annual Green Chemistry & Engineering Conference in Long Beach, California. The hybrid event was joined by more than 200 faculty, students, and industry members who committed to act for a more sustainable future through green chemistry.[28]

The first years of the GCC program were based on creating a community of practice, thus establishing a network of individuals and institutions. By investing in educators, developing green chemistry resources and tools, providing peer support networks, building strategic partnerships, and instilling inclusive initiatives at its core, the GCC program is now fostering a community with increased confidence to practice and teach green chemistry, equipped to drive transformative and systemic change in chemistry education across all aspects of the student journey. Therefore, 10 years after its launch, the GCC program has shifted toward supporting and empowering a community of transformation that fosters new practices towards green chemistry education that can be integrated into various institutions led by green chemistry educators worldwide.[29] Currently, more than 150 higher education institutions are part of the GCC program, reaching over 3300 faculty members and impacting about 840 000 students annually around the world (Fig. 1).[30] Funded by partner organizations and industries, Beyond Benign developed and implemented several initiatives to support the integration of green chemistry into the curricula and increase the accessibility of the field. Some of them are highlighted and described below. Through industry partner support, over $150 000 USD in funds have been given out to GCC signing institutions from 2019–2023 and the GCC program has doubled in size since 2019.

The 25 × 25 Initiative

To help create a local and long-lasting change in the U.S. chemistry educational system, Beyond Benign launched the 25 × 25 Initiative in 2021. This approach aims to provide support and resources to ensure that 25% of graduating U.S. chemists have a background in green chemistry by 2025.[31,32] Assessment of chemistry programs, recommendation of lessons to be incorporated into the curriculum, financial resources, and ongoing support for educators and staff are some strategies to increase the current percentage (12%) and achieve the proposed goal by 2025. Grant opportunities known as the Green Chemistry Education Challenge Awards were created through the 25 × 25 initiative for institutions participating in the GCC program to receive small grants to advance one-year or multi-year projects.[33] These projects focused on increasing the awareness of green chemistry on their campuses, supporting educators to expand their leadership and curriculum in green chemistry, fostering connections through its development, and further sharing of lessons and teaching.

For the 25 × 25 Initiative, a combined total of $55 000 USD (37% of total GCC grant funding) has been awarded to 8 institutions in the U.S. to drive awareness and improve the adoption of green chemistry locally and internationally, and these numbers continue to grow.[34–36] The first Green Chemistry Challenge Award winners (*i.e.*, Michigan State University; University of California, Berkeley; Southern University and Agricultural & Mechanical College) proposed the design of more than 10 teaching resources, thus helping to bring green

Fig. 1 A timeline of the Green Chemistry Commitment (GCC) program, which is composed of more than 150 higher education institutions worldwide as of December 31, 2023.

chemistry directly to an approximate number of 3000 students annually.[35–37] Michigan State University was able to evaluate and investigate the transition of its undergraduate organic course into a green chemistry project-based laboratory, reaching approximately 1200 students yearly.[36,38,39] In the Berkeley Center for Green Chemistry, faculty members, instructors, and graduate students at the institution worked on improving the sustainability of a chemistry experiment for its incorporation into an introductory organic chemistry class.[36] At Southern University and Agricultural & Mechanical College, chemistry and other science majors were, are and plan to be impacted by a complete reform of the chemistry departmental curriculum, where the implementation of green chemistry will be incorporated in every chemistry lecture and laboratory course.[36,37] By implementing these approaches, our award-winning institutions noticed increased student interest and appreciation of chemistry as much more than an academic subject due to an understanding of green chemistry's significance to our society and the environment.[31–34]

The Green Chemistry Teaching and Learning Community

While the GCC program has continued to grow globally since its launch in 2013, due to infrequent and high barriers to in-person events (conference fees, travel funds, COVID-19 pandemic restrictions), the GCC community has limited opportunities to connect. The need for an online community space was discussed by leaders of the GCC program during the 1st Annual GCC Summit in 2018 and during Beyond Benign focus groups in 2019 since it would allow the community of practice to lead and serve as a model for the greater chemistry community to transform education. In addition, the community also identified an opportunity for a space and resource repository, filling a gap left by the removal of the University of Oregon's GEMs (Greener Educational Materials) database,[10] an open-access database that housed green chemistry education materials until 2017.

Beyond Benign started efforts to address the need for resource sharing and effective peer-to-peer learning and information exchange with the larger green chemistry community (including K-12 educators, industry, government, and non-governmental organizations). In 2019, a collaboration with the American Chemical Society Green Chemistry Institute (ACS GCI) allowed the development of an online platform to promote resources, host discussions, and support a community of transformation around the field of green chemistry. Known as the Green Chemistry Teaching and Learning Community (GCTLC), the platform was officially launched in October 2023 and has since grown to include over 549 registered users (55% of which represent higher education students, administrators, and students) from 54 countries around the world.[40–43] Moreover, 39% of the faculty that serve as primary contacts for the GCC program at their institutions (59 institutions of 150) have joined the GCTLC platform to connect since its launch. Including additional faculty, staff, and students from GCC signing institutions, the total GCC program community represents 20% of the GCTLC membership database.

Members of the GCTLC can create user profiles, search for other educators and users worldwide, discuss in site-wide forums, post events to the GCTLC's calendar, add to the platform's job board, contribute to the GCTLC's open-access library of over 160 educational resources (including lab experiments, in-class activities, and course modules), and others.[40–43] The GCTLC membership database will serve as a recruitment tool for the GCC program, and the GCTLC group space will provide a networking and collaboration space for the Annual GCC Summit in 2024. The GCTLC will also serve as a tool for the Commitment program to foster and track its growth, amplify unique approaches of the GCC signers' regarding green chemistry incorporation, and further highlight gaps to fill in order to move the community forward.

The Minority Serving Institution Initiative

The Minority Serving Institution (MSI) Initiative focuses on improving the accessibility of green chemistry to students, faculty, and staff from underrepresented communities.[44] MSIs are higher education institutions in the U.S. unique in their missions to serve the needs of student populations with significant enrolment from minority groups.[45,46] Historically Black Colleges and Universities (HBCUs), Native Tribal Colleges and Universities (TCUs), Hispanic Serving Institutions (HSIs), and Asian American and Native American Pacific Islander-Serving Institutions (AANAPISIs) are examples of institutions founded to improve the access of minority communities to higher education.[45,46] As seen Fig. 2a, MSIs have been an essential part of the GCC program since its creation. However, the MSI Initiative promotes an intentional and additional layer of support for faculty, staff, and students at these institutions to provide equitable access to green chemistry education.

Since its launch, the MSI Initiative has been responsible for bringing more than 17 institutions in the U.S. dedicated to serving minority communities to the GCC program. Currently, 23% of the GCC signers are MSIs (Fig. 2b). The green chemistry journeys of these institutions are supported *via* dedicated professional development and grant opportunities. From the start of the MSI Initiative to the end of 2023, approximately \$52 000 USD in grants (35% of total GCC grant funding) have been awarded to educators and students to fund their green chemistry outreach, educational, and research initiatives. The proposed projects of these grant winners include: (i) curriculum reform and redesign to integrate green chemistry principles and practices; (ii) outreach initiatives to local communities and K-12 schools; (iii) events to raise green chemistry awareness on- and off-campus; (iv) creating new green chemistry majors and minors in chemistry programs; and (v) reforming chemistry laboratory spaces to facilitate green chemistry practices.

Breaking barriers: The international expansion of the Green Chemistry Commitment program

As seen in Fig. 2b, the majority of institutions within the GCC are MSIs and non-MSIs based within the U.S. (70%). This

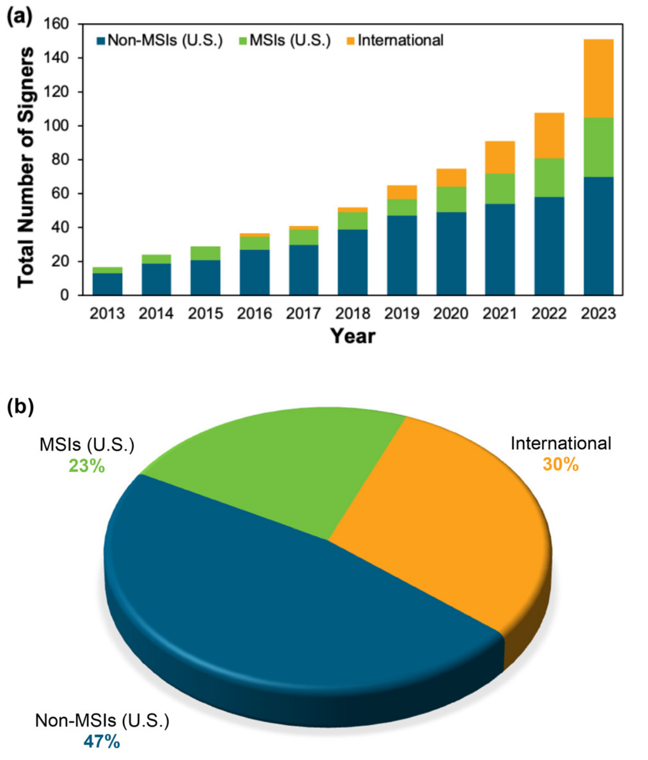

Fig. 2 (a) Total number of non-MSIs, MSIs, and institutions outside of the U.S. participating in the GCC program yearly since its launch and (b) distribution of GCC signers from MSIs, non-MSIs, and international institutions, as of December 31, 2023.

could be explained by Beyond Benign's office being initially located in the U.S. and the higher availability of green chemistry educational resources in English at the early stages of the GCC program. Through a combination of several factors, including the urgent need for sustainable actions, the expansion of the green chemistry field, increased funding, a growing number of green chemistry resources in different languages, and the establishment of a solid and engaging online community presence due to the COVID-19 pandemic, the GCC has observed a significant increase in the number of international signers.

The percentage of institutions outside of the U.S. committed to incorporating green chemistry education has doubled since 2020 (Fig. 2a), reaching a total of 30% in 2023. As seen in Fig. 3, the GCC program is currently incorporated in more than 15 countries across the world.[47] The improved accessibility to the Commitment program has allowed these signers to take a leadership role in their countries and, through a chain effect, inspire other institutions and individuals to act.[47,48] To promote and amplify the leadership of faculty and students within the international community of GCC signers, a total of $42 000 USD in funding (28% of total GCC grant funding) was awarded to 4 American Chemical Society Student Chapters and 8 institutions outside of the U.S. in 2023 through the Green Chemistry Education Challenge Awards.[33]

Integrating Green Chemistry in higher education

The impact of the Green Chemistry Commitment program

By including green chemistry in higher education, our society can ensure that our scientists are trained in the most responsible way to assess and design molecular species that are inherently safer for themselves and their communities. Many companies worldwide have established diverse sustainability strategies, which require chemists with skills to address the environmental and societal impacts of the processes and products created.[49–54] In fact, the growth in demand for green skills (22.4%) already surpassed the share of green talent in the workforce (12.3%) between 2022 and 2023, and this

Fig. 3 Worldwide distribution of institutions participating in the GCC program. More than 150 GCC signers are based in over 15 countries, with communities outside of the U.S. representing 30% of the total number of participating institutions as of December 31, 2023.

supply-demand disconnect is likely to rise considerably without further investments in the future workforce.[55] Moreover, the number of jobs for chemists specialized in green chemistry is expected to grow by 5% through 2029.[56] According to the International Labor Organization (ILO), skills development is the foundation of a green and just transition, with the most important changes in skills and occupation occurring at higher education levels.[57,58] In this sense, the integration of green chemistry in the curriculum can promote a coordinated approach to establishing a transition to a sustainable future that is also inclusive of all scientists and members of our society.

To assess the impact of the GCC program on the integration of green chemistry in higher education, as well as to understand the impact of signing institutions in the broad scientific community, a GCC Audit Questionnaire is realized annually.[47,48] For the 2022–2023 years, a total of 98 GCC signers (80% of participating institutions at the time the survey was conducted) shared the status of their green chemistry journeys in their higher education institutions, thus allowing Beyond Benign to evaluate patterns of where and how green chemistry is included in chemistry departments worldwide.[47]

Based on the 2022–2023 GCC Audit Questionnaire, 77% of the institutions participating in the GCC have increased their green chemistry teaching and practices since they joined the Commitment, and 94% are currently integrating green chemistry principles and practices in their teaching. This integration is also connected to broader societal issues (*e.g.*, health equity, social and environmental justice, climate change, and the United Nations Sustainable Development Goals[59]) in 69% of the respondents, thus highlighting that green chemistry is often shown by educators in their courses as a tool to practice sustainability. Regarding its local impact, the GCC program is also promoting the adoption of sustainability research and practices comprehensively: 61% of respondent institutions are incorporating green chemistry and sustainability at broader levels, while 19% plan to do so within the following year. 70% of the GCC signing institutions have active groups performing and researching green chemistry. By applying green chemistry, a significant majority of the committed institutions (92%) have also reduced the amount of waste generated in their teaching labs, thus decreasing costs while promoting a safer environment for the students enrolled.[47] The results and trends obtained during the 2022–2023 GCC Audit Questionnaire are summarized in Fig. 4.

Diverse approaches for Green Chemistry incorporation

The strategies for green chemistry integration in education are distinct, reflecting the diversity of institutions, locations, resources, and individuals in this global and long-lasting movement toward achieving a sustainable future at the molecular level.[60–77] Examples include Beyond Benign's higher education curricula and case studies,[78] the 'Green and Sustainable Chemistry Education Road Map' developed by the ACS GCI,[79] and the 'Specialized Manual on Green and Sustainable Chemistry Education and Learning' recently launched by the United Nations Environment Programme (UNEP).[80] These resources highlight the role of green chemistry in facilitating transformative changes in education and provide practical guidance, core competencies, and action steps for designing effective and systemic green chemistry learning.[79,80] Some of these strategies for incorporating green chemistry in the undergraduate, graduate, and postgraduate levels have been successfully implemented by institutions participating in the Commitment program to work on achieving the four GCC student learning objectives. A summary of these approaches can be found in Table 1.

Through the revision of the existing curriculum, green chemistry and/or toxicology modules can be included in chemistry courses, as well as in research projects and programs. One example is the integrated strategy performed by the

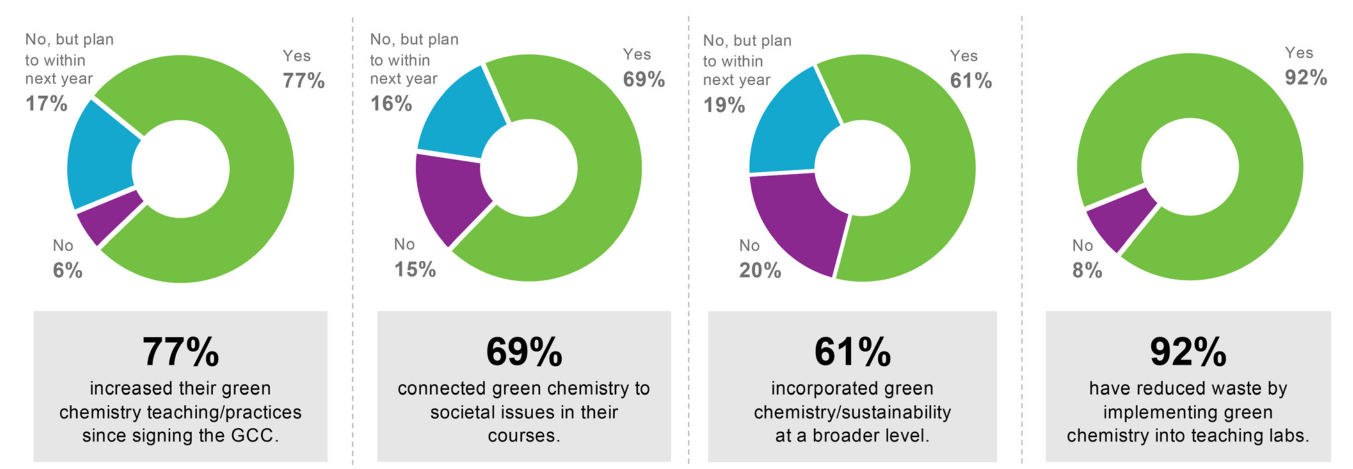

Fig. 4 Results from the 2022–2023 GCC Audit Questionnaire. The majority of GCC signers increased their green chemistry teaching and practices, connected green chemistry to societal issues, incorporated green chemistry and sustainability broader levels, and have reduced waste by implementing green chemistry in their teaching laboratories since joining the Commitment program.

Table 1 Examples of strategies taken by GCC signing institutions for integrating green chemistry in undergraduate, graduate, and postgraduate levels and promoting the adoption of the four student learning objectives of the Commitment program

Green chemistry adoption strategy	Actions and approaches performed
Revising existing curriculum	Inclusion of green chemistry throughout existing chemistry courses
	Integration of green chemistry exercises throughout lab courses
	Incorporation of green chemistry in research projects or programs
	Inclusion of toxicology and environmental health science modules in existing chemistry courses
Creating a new curriculum	Development of new courses dedicated to green chemistry
	Design of toxicology and environmental health science courses
	Development of a seminar series on green chemistry or toxicology
Using other institutional or external resources	Lectures on green chemistry or toxicology as part of a seminar series
	Encouragement of students to take elective courses in toxicology or environmental health sciences from other departments or institutions
Promoting student outreach	Organization of green chemistry outreach events
	Creation of green chemistry student chapters

University of Toronto (Canada), where a systems thinking approach is used to holistically embed green chemistry in the undergraduate curriculum and departmental culture.[63,64] Creating green chemistry courses is another approach for the field's incorporation in higher education institutions. The 'Green and Sustainable Chemistry' course at Washington College was one of the few green chemistry courses taught in the U.S. in 2005. Since then, the course was continuously revised and improved with the student body's help to provide them with meaningful and impactful training.[60–62] In this regard, students can further promote sustainable actions on their campus and help to reshape their environments and communities through green chemistry practice and advocacy. Green chemistry student-led organizations such as the Green Chemistry Initiative (GCI) also provide resources, promote sustainable research, share education practices, and organize outreach events, thus playing a fundamental role in incorporating green chemistry principles and practices by the chemistry community and the general public.[74,75] Other institutional or external resources through seminars or elective courses also help in green chemistry integration. The GCC community is comprised of many experts from diverse backgrounds and subdisciplines of chemistry who could serve as guest speakers, promoting cross-campus collaborations locally and globally.

Regardless of the approach taken, it is important to highlight that the initiative of teaching and practicing green chemistry does not require a complete and throughout renovation of the chemistry curriculum. Green chemistry adoption could be performed by simply practicing and teaching traditional concepts through the 'lens of green chemistry'.[81,82] Besides being promoted by a wide range of resources highlighted herein, this low-barrier incorporation of more sustainable teaching, research, and practices is also supported by the existence of a proactive and engaging community of green chemistry practitioners and educators supported by the GCC program across the globe.[83–103]

A shift in chemistry education

The ability of green chemistry to interconnect social, economic, and environmental aspects of our society to find solutions for global concerns is relatable and engaging to students. A previous study assessing students' understanding and value of green chemistry shows that students recognize green chemistry as an important connection to be taken to another class, even being identified as the most valuable part of the course by some of them.[66] Surveys conducted by the Students Organizing for Sustainability (SOS) International and the Royal Society of Chemistry (RSC) also demonstrate that students are expected to be educated about sustainability and climate change in their chemistry courses, and that educational institutions (*e.g.*, schools, colleges, and universities) have the biggest responsibility to teach them about how to address these issues and challenges.[104,105]

In the U.S., green chemistry education began as a grassroots movement that has led to significant policy changes, as it is now considered a requirement for undergraduate programs to obtain American Chemical Society (ACS) approval. Currently, 701 undergraduate chemistry programs are approved by the ACS, thus emphasizing their work in giving students the skills necessary to be competitive in a global economy. The ACS approval is overseen by the ACS Committee on Professional Training (CPT) through the ACS Guidelines for Bachelor's Degree Programs,[106] which are divided into 'critical requirements,' 'normal expectations,' and 'markers of excellence.' These categories provide programs with the opportunity to develop tracks that are appropriate to the educational missions of their institutions.

In 2018, the ACS CPT created a green chemistry supplement to the ACS Guidelines for Bachelor's Degree Programs to motivate chemistry educators to adopt green chemistry in their coursework.[107] The 'Green Chemistry in the Curriculum' supplement provided context and guidance through conceptual topics in green chemistry and illustrative examples of green chemistry integration within traditional chemistry subdisciplines (*e.g.*, general, organic, inorganic, analytical, physical, and biochemistry). As of 2023, green chemistry has been fully integrated into the ACS Guidelines for Undergraduate Programs, and a working knowledge of the 12 principles of green chemistry is now a 'critical requirement' for a chemistry program to obtain ACS approval.[108] Curricular green chemistry and sustainability case studies that demonstrate the connection between chemical, environmental health, regulatory, and business considerations should become 'normal expectations'. For chemistry programs wishing to acquire optional 'markers of excellence' that display institutional practices characteristic of supportive innovation and inclusive education, students should further understand and evaluate the environmental, social, and health of a chemical product over its lifecycle.

According to the UNEP Specialized Manual on Green and Sustainable Chemistry, 'the time is right to scale up action for green and sustainable chemistry education',[80] and the recently released ACS Guidelines for Undergraduate Programs are reflective of this trend. Achieving a sustainable future through green chemistry education represents a transformative step that requires collaboration between different individuals, approaches, sectors, organizations, and institutions within our society. The guidelines recently released by the ACS are hopefully the beginning of a movement promoted by national organizations across the world to responsibly prepare the next generation of scientists and citizens. Examples include the Royal Society of Chemistry (RSC), which has recently incorporated green chemistry into its accreditation criteria.[109]

Toward a community of transformation

Communities of practice are essential to provide support mechanisms for creating systemic change. In addition to allowing access to resources and technical expertise for content areas, there are social benefits by creating a sense of community. Communities focused on STEM (science, technology, engineering, and math) education reform initiatives have led to transformational results.[29] As the growing community of green chemistry practitioners shifts towards a community of transformation, the GCC, along with the GCTLC as a key resource, aims to provide the support needed for educators to transform their chemistry teaching and practice. A community of transformation has three components: (i) a compelling philosophy, (ii) a living integration of the philosophy to create a new world of practice, and (iii) a network of peers to break isolation and provide support to sustain changes.[29] By fostering a community of practice, the GCC provides a supportive network of faculty and institutions invested in transitioning their teaching and practice to green chemistry practices.

The GCC aims to support the community of transformation where the philosophy of green chemistry becomes a living methodology applied throughout academia, with a network of invested educators and institutions providing support to sustain long-term changes. The GCC is a transformative step that can lead to the integration of green chemistry throughout chemistry programs by practitioners globally. GCC institutions will lead the way toward the ultimate goal of improved chemistry education for all students, thus preparing them for careers that empower them to use the tools of chemistry to create a sustainable planet.

Conflicts of interest

There are no conflicts to declare.

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References

1 P. T. Anastas and J. C. Warner, *Green chemistry: Theory and practice*, Oxford University Press, England, 1998.
2 K. M. Doxsee and J. E. Hutchison, *Green Organic Chemistry: Strategies, Tools, and Laboratory Experiments*, Brooks Cole, United States, 2003.
3 M. Kirchhoff and M. A. Ryan, *Greener Approaches to Undergraduate Chemistry Experiments*, American Chemical Society, United States, 2002.
4 Green Chemistry, Royal Society of Chemistry Journals, **https://www.rsc.org/journals-books-databases/about-journals/green-chemistry/**, (accessed Jan. 28, 2023).
5 Green Chemistry Letters and Reviews, Taylor & Francis, **https://www.tandfonline.com/journals/tgcl20**, (accessed Jan. 28, 2024).
6 Green Chemistry Award, Royal Society of Chemistry, **https://www.rsc.org/prizes-funding/prizes/archives/green-chemistry-award/**, (accessed Jan. 28, 2024).
7 Green Chemistry Awards, Chemical Institute of Canada, **https://www.cheminst.ca/awards/cgcen/**, (accessed Jan. 28, 2024).
8 Green Chemistry, United States Environmental Protection Agency (EPA), **https://www.epa.gov/greenchemistry**, (accessed Jan. 28, 2024).
9 Green Chemistry Funding & Awards, American Chemical Society, **https://www.acs.org/funding/green-chemistry.html**, (accessed Jan. 28, 2024).
10 J. A. Haack and J. E. Hutchison, *ACS Sustainable Chem. Eng.*, 2016, **4**, 5889–5896.
11 Change Chemistry, **https://member.changechemistry.org**, (accessed Jan. 29, 2024).
12 Green Chemistry Network Centre (GCNC), **https://www.gcnc.in**, (accessed Jan. 29, 2024).

13 Canadian Green Chemistry Network and Engineering (CGCEN), https://www.cheminst.ca/communities/divisions/cgcen/, (accessed Jan. 29, 2024).
14 Network of Early-Career Sustainable Scientists and Engineers, https://www.sustainablescientists.org, (accessed Jan. 29, 2024).
15 GREEN-CHEM, https://www.ugent.be/greenchem/en/about, (accessed Jan. 29, 2024).
16 CIFamily, Career, Transfer, Diversity, UniSysCat Berlin, https://www.unisyscat.de/career/transfer/cifamily, (accessed Jan. 30, 2024).
17 V. Zuin and L. Mammino, *Worldwide Trends in Green Chemistry Education*, The Royal Society of Chemistry, Cambridge, UK, 2015.
18 M.-Y. Wang, X.-Y. Li and L.-N. He, *Curr. Opin. Green Sustainable Chem.*, 2018, **13**, 123–129.
19 A. S. Cannon, K. R. Anderson, M. C. Enright, D. G. Kleinsasser, A. R. Klotz, N. J. O'Neil and L. J. Tucker, *J. Chem. Educ.*, 2023, **100**, 2224–2232.
20 A. S. Cannon, A. E. Keirstead, R. Hudson, I. J. Levy, J. MacKellar, M. Enright, K. R. Anderson and E. M. Howson, *J. Chem. Educ.*, 2021, **98**, 71–77.
21 Green Chemistry Curriculum, Beyond Benign, https://www.beyondbenign.org/curriculum/, (accessed Jan. 28, 2024).
22 H. R. Hungerford and T. L. Volk, *J. Environ. Educ.*, 1990, **21**, 8–21.
23 S. E. Shadle, Y. Liu, J. E. Lewis and V. Minderhout, *Innov. High. Educ.*, 2018, **43**, 475–490.
24 P. C. Nahlik, *Cultivating Teacher Expertise in the Landscape of Green Chemistry: The Development of Pedagogical Content Knowledge in Beyond Benign's Lead Teacher Program*, Loyola University Chicago, Doctor of Philosophy Dissertation, 2022.
25 The Green Chemistry Commitment, Beyond Benign, https://www.beyondbenign.org/he-green-chemistry-commitment/, (accessed July 10, 2023).
26 A. S. Cannon and I. J. Levy, in *The Promise of Chemical Education: Addressing our Students' Needs*, American Chemical Society, 2015, ch. 9, vol. 1193, pp. 115–125.
27 The Presidents' Climate Leadership Commitments, Climate Leadership Statement, Second Nature, https://secondnature.org/signatory-handbook/the-commitments/, (accessed July 11, 2023).
28 10 Years of Embracing Inspiration and Building Community: Reflecting on the 2023 Green Chemistry Commitment Summit, Beyond Benign, https://www.beyondbenign.org/news/10-years-of-embracing-inspiration-and-building-community-reflecting-on-the-2023-green-chemistry-commitment-summit/, (accessed Nov. 12, 2023).
29 A. Kezar and S. Gehrke, *Communities of Transformation and their Work Scaling STEM Reform*, Pullias Center for Higher Education, Rossier School of Education, University of Southern California, 2015.
30 Who's Committed, Beyond Benign, https://www.beyondbenign.org/he-whos-committed/, (accessed July 25, 2023).
31 Committed to Green Chemistry Education, Dow, https://corporate.dow.com/en-us/science-and-sustainability/2025-goals/earth-day/beyond-benign-partnership.html, (accessed Nov. 23, 2023).
32 Beyond Benign Launches Its Green Chemistry Commitment 25 × 25 Initiative, Beyond Benign, https://www.beyondbenign.org/news/beyond-benign-launches-its-green-chemistry-commitment-25x25-initiative/, (accessed Nov. 23, 2023).
33 Green Chemistry Education Challenge Awards, Beyond Benign, https://www.beyondbenign.org/he-gc-challenge-awards/, (accessed Jan. 29, 2024).
34 Empowering Tomorrow's Innovators: Celebrating the Impactful Initiatives of the 2022–2023 Green Chemistry Education Challenge Award Winners, Beyond Benign, https://www.beyondbenign.org/news/empowering-tomorrows-innovators-celebrating-the-impactful-initiatives-of-the-2022-2023-green-chemistry-education-challenge-award-winners/, (accessed Dec. 4, 2023).
35 Preparing the Incoming Workforce for a Sustainable Future Through Green Chemistry, Beyond Benign, https://www.beyondbenign.org/news/preparing-the-incoming-workforce-for-a-sustainable-future-through-green-chemistry/, (accessed Dec. 4, 2023).
36 Dow Green Chemistry Education Challenge Award Winners Catalyze Green Chemistry at Higher Education Institutions, Beyond Benign, https://www.beyondbenign.org/news/dow-green-chemistry-education-challenge-award-winners-catalyze-green-chemistry-at-higher-education-institutions/, (accessed Dec. 4, 2023).
37 A Growing Community of Green Chemists at Southern University - An Interview with Conrad Jones, Beyond Benign, https://www.beyondbenign.org/news/a-growing-community-of-green-chemists-at-southern-university/, (accessed Jan. 6, 2024).
38 Dr Veronica Mengqi Zhang: Gaining Resources, Support & Opportunities Through the GCC Community, Community News, Beyond Benign, https://www.beyondbenign.org/news/dr-veronica-mengqi-zhang-gaining-resources-support-opportunities-through-the-gcc-community/, (Jan. 30, 2024).
39 M. Zhang, E. L. Day, H. McFall-Boegeman, S. J. Petritis and M. M. Cooper, *Green Chem. Lett. Rev.*, 2023, **16**, 2183781.
40 Announcing the Launch of the Green Chemistry Teaching and Learning Community (GCTLC), Send2Press Newswire, https://www.send2press.com/wire/announcing-the-launch-of-the-green-chemistry-teaching-and-learning-community-gctlc/, (accessed Nov. 23, 2023).
41 . Green Chemistry Teaching and Learning Community (GCTLC), Environmental News Bits, https://envnewsbits.info/2023/10/10/green-chemistry-teaching-and-learning-community-gctlc/, (Nov. 23, 2023).
42 Announcing the Launch of the Green Chemistry Teaching and Learning Community (GCTLC), Beyond Benign, https://www.beyondbenign.org/news/announcing-the-launch-of-the-green-chemistry-teaching-and-learning-community-gctlc/, (accessed Nov. 23, 2023).

43 J. Moir, Building Space for Community: An Update on the GCTLC, ACS Network, GCI Nexus Blog, https://communities.acs.org/t5/GCI-Nexus-Blog/Building-Space-for-Community-An-Update-on-the-GCTLC/ba-p/86371, (accessed Nov. 23, 2023).
44 Beyond Benign Launches Initiative to Support Green Chemistry Educators at Minority-Serving Higher Education Institutions, Beyond Benign, https://www.beyondbenign.org/news/beyond-benign-launches-initiative-to-support-green-chemistry-educators-at-minority-serving-higher-education-institutions/, (accessed Dec. 7, 2023).
45 C. Conrad and M. Gasman, *Educating a Diverse Nation*, Harvard University Press, Cambridge, MA and London, England, 2015.
46 E. M. O'Brien and C. Zudak, *New Dir. High. Educ.*, 2002, **1998**, 5–15.
47 Dr. N. J. O'Neil, Dr. N. K. Obhi and Dr. J. L. Vidal, *2022–2023 Status Report, Green Chemistry Commitment Audit Results*, Beyond Benign, 2023.
48 Dr. N. J. O'Neil and Dr. N. K. Obhi, *2021–2022 Status Report, Green Chemistry Commitment Audit Results*, Beyond Benign, 2022.
49 Science and Sustainability, 2025 Sustainability Goals, Dow, https://corporate.dow.com/en-us/science-and-sustainability/2025-goals.html, (accessed Jan. 8, 2024).
50 Sustainability, Environment, Lego, https://www.lego.com/en-us/sustainability/environment, (accessed Jan. 8, 2024).
51 Responsibility: Environment, Sustainable Policy, Biogen, https://www.biogen.com/responsibility/environment.html, (accessed Jan. 8, 2024).
52 Greener Products & Solutions, MilliporeSigma, https://www.sigmaaldrich.com/CA/en/life-science/ssbi/greener-products-solutions, (accessed Jan. 8, 2024).
53 *2023 Environmental Progress Report*, Apple, 2023.
54 2022 Corporate Responsibility (ESG) Report, ICL, https://icl-group-sustainability.com, (accessed Jan. 8, 2024).
55 *Global Green Skills Report* 2023, LinkedIn Economic Graph, 2023.
56 B. Lawhorn, Where the Green Jobs Grow, U.S. Department of Labor, https://blog.dol.gov/2021/04/21/where-the-green-jobs-grow, (accessed Jan. 9, 2024).
57 *World Employment and Social Outlook 2018: Greening With Jobs*, International Labour Organization, 2018.
58 O. Strietska-Ilina and T. Mahmud, *Skills for a Greener Future: A Global View Based on 32 Country Studies*, International Labour Organization, 2019.
59 The 17 Goals, Sustainable Development, The United Nations, https://sdgs.un.org/goals, (accessed Feb. 20, 2024).
60 Green Chemistry Commitment Case Study: Washington College, https://www.beyondbenign.org/bbdocs/pdfs/Washington_College_Case_Study_2020_final.pdf, (accessed July 14, 2023).
61 A. E. Marteel-Parrish, *J. Chem. Educ.*, 2007, **84**, 245–247.
62 A. E. Marteel-Parrish, *J. Chem. Educ.*, 2014, **91**, 1084–1086.
63 Green Chemistry Commitment Case Study: University of Toronto, https://www.beyondbenign.org/bbdocs/pdfs/University_of_Toronto_Case_Study_2020.pdf, (accessed July 14, 2023).
64 A. P. Dicks, J. C. D'eon, B. Morra, C. Kutas Chisu, K. B. Quinlan and A. S. Cannon, *J. Chem. Educ.*, 2019, **96**, 2836–2844.
65 L. Abraham, in *Green Chemistry*, ed. B. Mark Anthony and K. Steven, De Gruyter, Berlin, Boston, 2022, pp. 3–44.
66 L. B. Armstrong, M. C. Rivas, Z. Zhou, L. M. Irie, G. A. Kerstiens, M. T. Robak, M. C. Douskey and A. M. Baranger, *J. Chem. Educ.*, 2019, **96**, 2410–2419.
67 A. Ashley-Oyewole, in *Green Chemistry*, ed. B. Mark Anthony and K. Steven, De Gruyter, Berlin, Boston, 2022, pp. 81–94.
68 K. B. Aubrecht, M. Bourgeois, E. J. Brush, J. MacKellar and J. E. Wissinger, *J. Chem. Educ.*, 2019, **96**, 2872–2880.
69 R. M. Bouldin and Z. Folchman-Wagner, *J. Chem. Educ.*, 2019, **96**, 647–651.
70 F. A. Etzkorn and J. L. Ferguson, *Angew. Chem., Int. Ed.*, 2023, **62**(2), e202209768.
71 K. Grieger and A. Leontyev, *J. Chem. Educ.*, 2020, **97**, 2657–2663.
72 K. Grieger and A. Leontyev, *J. Chem. Educ.*, 2021, **98**, 2881–2891.
73 A. E. Waked, K. Z. Demmans, R. F. Hems, L. M. Reyes, I. Mallov, E. Daley, L. B. Hoch, M. L. Mastronardi, B. J. De La Franier, N. Borduas-Dedekind and A. P. Dicks, *Green Chem. Lett. Rev.*, 2019, **12**, 187.
74 D. J. Swartling, in *Building and Maintaining Award-Winning ACS Student Member Chapters Volume 1: Holistic Viewpoints*, American Chemical Society, 2016, ch. 7, vol. 1229, pp. 91–102.
75 M. V. Wright and A. E. Keirstead, in *Building and Maintaining Award-Winning ACS Student Member Chapters Volume 3*, American Chemical Society, 2018, ch. 10, vol. 1278, pp. 115–125.
76 V. G. Zuin, M. L. Segatto, D. P. Zandonai, G. M. Grosseli, A. Stahl, K. Zanotti and R. S. Andrade, *J. Chem. Educ.*, 2019, **96**, 2975–2983.
77 S. M. Reed and J. E. Hutchison, *J. Chem. Educ.*, 2000, **77**, 1627–1629.
78 Higher Education Curriculum Topics, Higher Ed, Beyond Benign, https://www.beyondbenign.org/cur-highered/, (accessed Jan. 30, 2024).
79 J. J. MacKellar, D. J. C. Constable, M. M. Kirchhoff, J. E. Hutchison and E. Beckman, *J. Chem. Educ.*, 2020, **97**, 2104–2113.
80 A. Halpaap and C. Hannahan, *UNEP Specialized Manual on Green and Sustainable Chemistry Education and Learning*, United Nations Environment Programme (UNEP), 2023.
81 A. P. Dicks, *Green Anal. Chem.*, 2023, **7**, 100082.
82 T. E. Goodwin, *J. Chem. Educ.*, 2004, **81**, 1187–1190.
83 O. B. Andrew, J. Sherwood and G. A. Hurst, *J. Chem. Educ.*, 2022, **99**, 3277–3282.

84 L. B. Armstrong, L. M. Irie, K. Chou, M. Rivas, M. C. Douskey and A. M. Baranger, *Chem. Educ. Res. Pract.*, 2024, **25**, 115–132.
85 L. D. Bastin, M. Nigam, S. Martinus, J. E. Maloney, L. L. Benyack and B. Gainer, *Green Chem. Lett. Rev.*, 2019, **12**, 127–135.
86 H. L. Buckley, A. R. Beck, M. J. Mulvihill and M. C. Douskey, *J. Chem. Educ.*, 2013, **90**, 771–774.
87 J. D'eon and J. R. Silverman, *Green Chem. Lett. Rev.*, 2023, **16**, 2185109.
88 M. Dilip and M. E. Kerr, *Phys. Sci. Rev.*, 2016, **1**, 20160078.
89 R. F. Gómez-Biagi and A. P. Dicks, *J. Chem. Educ.*, 2015, **92**, 1938–1942.
90 G. A. Hurst, in *Integrating Green and Sustainable Chemistry Principles into Education*, ed. A. P. Dicks and L. D. Bastin, Elsevier, 2019, pp. 205–228.
91 M. Karpudewan, W. M. Roth and D. Sinniah, *Chem. Educ. Res. Pract.*, 2016, **17**, 893–901.
92 D. G. Kovacs, R. R. Rediske, S. Marty, P. J. Spencer, D. Wilson and B. Landenberger, *Green Chem. Lett. Rev.*, 2019, **12**, 136–146.
93 G. A. Lasker and E. J. Brush, *Green Chem. Lett. Rev.*, 2019, **12**, 168–177.
94 D. B. Lee, *Green Chem. Lett. Rev.*, 2019, **12**, 107–116.
95 N. E. Lee, R. Gurney and L. Soltzberg, *J. Chem. Educ.*, 2014, **91**, 1001–1008.
96 A. Marteel-Parrish and H. Harvey, *Green Chem. Lett. Rev.*, 2019, **12**, 147–160.
97 J. L. Miller, M. T. Wentzel, J. H. Clark and G. A. Hurst, *J. Chem. Educ.*, 2019, **96**, 3006–3013.
98 B. Morra, *J. Chem. Educ.*, 2018, **95**, 2212–2215.
99 M. A. Nitka, K. E. Zerbee, J. M. Dee, M. A. Cranswick, E. P. Zovinka and J. R. De Backere, *Green Chem. Lett. Rev.*, 2023, **16**, 2164700.
100 N. K. Obhi, I. Mallov, N. Borduas-Dedekind, S. A. L. Rousseaux and A. P. Dicks, *J. Chem. Educ.*, 2019, **96**, 93–99.
101 J. J. Palesch, B. C. Gilles, J. Chycota, M. K. Haj, G. W. Fahnhorst and J. E. Wissinger, *Green Chem. Lett. Rev.*, 2019, **12**, 117–126.
102 S. C. Purcell, P. Pande, Y. Lin, E. J. Rivera, U. L. Paw, L. M. Smallwood, G. A. Kerstiens, L. B. Armstrong, M. T. Robak, A. M. Baranger and M. C. Douskey, *J. Chem. Educ.*, 2016, **93**, 1422–1427.
103 K. M. D. Reyes, K. Bruce and S. Shetranjiwalla, *J. Chem. Educ.*, 2023, **100**, 209–220.
104 *Students, sustainability and education*, Students Organizing for Sustainability (SOS) International, 2021.
105 *Green shoots: A sustainable chemistry curriculum for a sustainable planet*, Royal Society of Chemistry (RSC), 2021.
106 ACS Guidelines for Bachelor's Degree Programs, American Chemical Society, **https://www.acs.org/education/policies/acs-approval-program/guidelines.html**, (accessed Jan. 27, 2023).
107 *Green Chemistry in the Curriculum*, American Chemical Society, ACS Committee on Professional Training, 2018.
108 *2023 ACS Guidelines for Undergraduate Programs*, American Chemical Society, ACS Committee on Professional Training, 2023.
109 Degree Accreditation, Royal Society of Chemistry, **https://www.rsc.org/membership-and-community/degree-accreditation/**, (accessed Feb. 20, 2024).
110 Partnerships, About Us, Beyond Benign, **https://www.beyondbenign.org/about-partnerships/**(accessed Jan. 31, 2024).
111 Founding Sponsors of the GCTLC, GCTLC, **https://gctlc.org/founding-sponsors-gctlc**, (accessed Jan. 31, 2024).

