Green and sustainable chemistry education: Nurturing a new generation of chemists

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From chemistry to green chemistry and green and sustainable chemistry education

Historically, toxicology and concerns for protecting human health and the environment have received limited attention in education in general and in chemistry classrooms in particular. A good example is that many critical sides of the use of certain chemicals were known in the scientific literature for long time, but were discussed neither in the public nor in education until the 1960s. After 1962, when the famous novel *Silent Spring* by Rachel Carson was published, public awareness started growing. The book deals with the risks of synthetic pesticides, especially DDT, for the environment and along the food chain also for human beings. The book sensitised the public about how mankind is treating the environment more than hardly any book did before. This publication became an influencing factor for political debate and can be considered a major impulse that from the early 1970s the use of DDT in agriculture became prohibited in most Western countries. A corresponding paradigm shift took place throughout the second half of the 20^{th} century towards pollution prevention starting from the Western countries. In 1990, the US Congress issued the Pollution Prevention Act. The act stated that pollution should be reduced or totally prevented at the source and recycled in an environmentally safe manner whenever feasible. Unavoidable pollution was suggested to be treated and disposed in an environmentally safe manner. In 1991, the Environmental Protection Agency (EPA) took up this idea as one of its guiding principles. These two events became starting points of what was later known as green chemistry.

Green chemistry was established in collaboration between the US government, Industry, and Academia. Paul Anastas and John Warner became founders of a new philosophy of chemistry by defining 12 principles that were suggested to be a framework for more environmentally friendly chemistry. In 1998 Warner and Anastas published the seminal book 'Green Chemistry: theory and practice'. This book provided a precise definition to green chemistry and justified its twelve principles. Anastas was the director of the U.S. Green Chemistry Programme at the EPA while John Warner turned his focus to education. He worked on education for the new generation of chemists respecting the green chemistry principles. In 1997, he was the founder of the first Ph.D. programme in green chemistry in the world at the Centre for Green Chemistry at the University of Massachusetts, Boston, USA. Later, Warner founded the non-profit foundation Beyond Benign to promote K-12 science education and community outreach as well as to initiate educational reform (e.g. Cannon and Warner 2011).

From the 1990s, chemistry education started reflecting the conceptual transition towards green chemistry (Collins 1995). The development of green chemistry and related educational approaches and curricula go hand in hand. The early 2000s saw also the proliferation of the new ideas mainly under the label of green chemistry in the scientific community, in particular in the United States, as demonstrated for example when the Green Chemistry Institute became a part of the American Chemical Society (ACS) (ACS n.d.). Both developments are based in a growing awareness of the adverse effects of certain chemicals.

Chemistry teaching curricula in several countries started to be revisited (Anastas 2015; Eilks and Zuin 2018). Subsequently, a growing number of universities incorporated green chemistry in their curricula, mainly for organic synthesis, and gradually incorporating the 12 GC principles into regular chemistry courses. Today, however, still a limited number of schools and universities worldwide have operated this process and the approaches for doing so vary greatly. There are universities that created whole courses on green chemistry, others started 'greening' their labs, and first teaching materials became available. Teachers and university educators, however, still struggle with how to incorporate GSC into their teaching.

There are still lacks in building the capacity of school teachers and university educators to make them confident to incorporate GSCE into their courses. There is still not sufficient support, networks or resources available for integrating green chemistry into the chemistry classroom, teachers claim a lack of corresponding strategies and course materials beyond single examples (e.g. Burmeister, Schmidt-Jacob and Eilks 2013). Also a look in educational standards or assessment guidelines, like the Anchoring Concept Content Maps by the ACS Exams Institute in the USA (e.g. Holme and Murphy 2012, and later updated versions), shows that there is still quite limited GSC content.

Nevertheless, one can say that the first elements of green chemistry education have been solidly established in many universities from all over the world (Eilks and Zuin 2018) and are being promoted by companies, governments, non-governmental organisations worldwide, and cross-sectional networks. Further justification and theoretical foundation was developed that connected green chemistry with different traditions and philosophies of education, e.g. eco-reflexive education (e.g. Sjöström, Eilks and Zuin 2018; Sjöström and Talanquer 2018). This also connected green chemistry to the movement of education for sustainable development in the Agenda 21 issued by the United Nations in 1992 (Burmeister, Rauch and Eilks 2012). This was paralleled by the integration of very similar ideas under the label of sustainable chemistry education in university and other curricula. Implementing this term is, however, a more recent phenomenon based on a suggestion by the OECD in 1999 that basically started in Europe and from industry.

An increasing number of academic institutions have now embraced the concept of 'green chemistry', and the more comprehensive related to sustainable chemistry, however, is used more rarely, e.g. at the Leuphana University Lüneburg (Germany). Despite these developments, there is still huge potential and need to further mainstream green and sustainable chemistry education (GSCE), the term that is now supported by the Green Chemistry Institute of the ACS and that will be used in this paper to respect both concepts as described above with their differences and parallels.

Green and sustainable chemistry education (GSCE) in a wide range of institutions and curricula

The concepts and principles of GSCE may feed into education at various levels and different settings, including high schools, universities, and professional education. As outlined below, GSCE has been introduced at an increasing number of research institutions and universities, both for the training of future chemists (e.g. Levy and Middlecamp 2015; Eilks and Zuin 2018), as well as of chemistry teachers (e.g. Zuin 2010; Burmeister and Eilks 2013). Various institutions have developed tools and materials to allow the integration of green and sustainable chemistry at high school and even elementary levels (e.g. ACS, n.d.; Beyond Benign n.d.; Burmeister, Rauch and Eilks 2012; Juntunen and Aksela 2013a) and to adequately address toxicology in the classroom (Cannon *et al.* 2017). For example, in the context of the UNESCO 'World Decade for Education for Sustainable Development', various learning materials for secondary education and universities were developed addressing topics related to green and sustainable chemistry (e.g, Zuin and Mammino 2015; Burmeister and Eilks 2012) and there is hope that this development continues framed by the Global Action Plan.

Box 1.1: Green and sustainable chemistry education at a high school

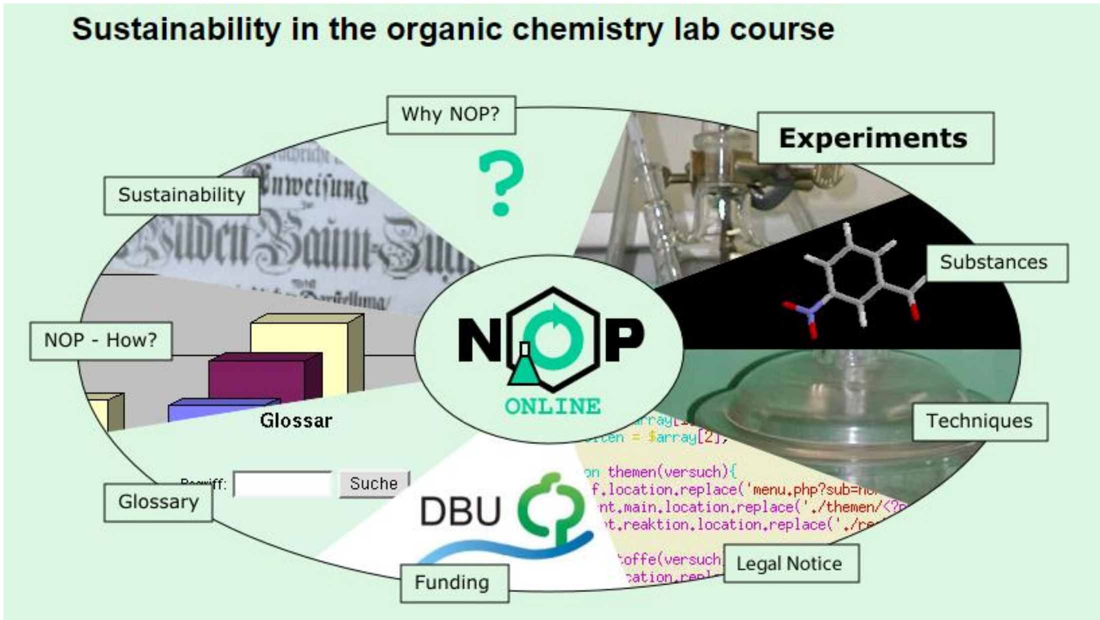
As an example, Aubrecht *et al.* (2015) describe the content of a series of day-long field trips for high school students to a university that connect chemistry content to issues of sustainability. The experiments focused on environmental degradation, energy production, and green chemistry, and they have been modified from published procedures so that the length and scope would be appropriate for the format and audience, from high school to university students, as shown in the table 1.1.

Table 1.1: Sustainable chemistry teaching laboratories content (Adapted from Aubrecht *et al.* 2015).

Theme	Laboratory Topic	Primary Chemistry Concepts	Connections to Sustainability
Environmental degradation	Interaction of acid rain with minerals	Titrations, neutralization reactions, metal ion solubility	Sources and impacts of acid rain, ocean acidification, mitigation efforts
Energy production	Preparation and use of dye-sensitized solar cells	Semiconductors, doping, silicon and dye-sensitized photovoltaic cells	Solar energy, stabilization wedges approach to reduce greenhouse gas emissions
Green chemistry	Synthesis of a biodegradable polymer and recycling of PETE	Polymers, line-angle functional groups, IR spectroscopy	Renewable feedstocks, biodegradability, “cradle to cradle” design, green chemistry

Ranke, Bahadir, Eissen and König (2008) report the development of a new lab-course for higher organic chemistry education: Aspects of efficiency and sustainability of reactions as well as toxicological and ecotoxicological knowledge were added to the content of teaching. Students are encouraged to plan, set up, and reflect organic laboratory activities while taking into account any effects on the environment and human beings. Another good example is the NOP (n.d.), an internet database that provides additional materials about laboratory procedures, toxicity data, alternative reaction routes, energy efficiency, and more to assess chemical reactions in wide sense. The course is available online and provides all materials in 11 different languages, among them English, Spanish or Russian.

Figure 1.1: Proposal of GSCE for higher organic chemistry lab course for the new millennium (NOP n.d.).



Green and sustainable chemistry education in teacher education

In the last 20 years, the inclusion of GSC has been studied and implemented in a number of countries, also in some developing ones (Zuin 2013). In Germany, for instance, Burmeister and Eilks (2013) described the cyclical design of a course module for secondary teacher education on GSCE at the University of Bremen. The module encompasses a combination of a change in the curriculum and the implementation of innovative pedagogies. A course is suggested with six sessions coming from general concepts of sustainability, via a *WebQuest* on green chemistry in research and industry, towards contemplation with educational policy documents and concrete teaching examples to integrate chemistry teaching with sustainability education.

Table 1.2: Chemistry teacher education for GSCE (Burmeister and Eilks 2013)

Session 1	Assessing a priori knowledge and attitudes towards sustainability and ESD using a research questionnaire Lecture on the historical genesis and modern concepts of sustainability Overview on the course and introduction to *WebQuest* for the issues of sustainability and green chemistry
Session 2	*WebQuest* on issues of sustainability, the concept of Green Chemistry and its perception in society Role playing of different views towards Green Chemistry, inspired by a *WebQuest*
Session 3	Jigsaw classroom on educational policy papers about ESD in German school education
Session 4	Analysing a lesson plan on teaching about plastics with an ESD focus, which mimics the product testing method in order to evaluate plastics in the foreground of sustainability criteria

Session 5	Facultative: Further analysis and discussion of teaching materials Facultative: A board game based on Green Chemistry in the chemical industry
Session 6	Lecture presentation summing up the course content Lecture presentation about basic models how to connect ESD and chemistry education Self-assessment of learning success with reference to the initial questionnaire and data about student teachers' knowledge on sustainability and ESD from the accompanying research Reflection of the course content and structure

2. Education reform gaining momentum in many countries, but some regions lagging behind

The extent to which GSCE has reached the general public, or has had an impact on large-scale behaviour patterns, is considered yet limited (Mammino 2015, Beyond Benign n.d.). Similarly, the inclusion of green and sustainable chemistry in university curricula is in many cases still confined to events, summer schools, short courses, one-off activities and the inclusion of specific elements of GSCE in existing courses (Leitner 2004; Zuin 2012).

Meanwhile, recent years have seen a momentum to mainstream GSCE in academia. Various activities started to grow (Andraos and Dicks 2012), and international conferences are now being organised on a regular basis, including in developing countries. Examples include IUPAC's 'International Conference on Green Chemistry'; the 'Annual Green Chemistry & Engineering Conference' (ACS); 'International Conference Green and Sustainable Chemistry' (global green chemistry community); 'Green and Sustainable Chemistry Conference' (Leuphana University together with Elsevier, Germany); and the 'Asia-Oceania Conference on Green and Sustainable Chemistry' and many others. Despite the inclusion of some sessions addressed to education purposes at these conferences, their contents do not seep into other sessions or seem to be a major thread of curricular innovation.

There are also an increasing number of books and journals focusing on green and sustainable chemistry (e.g. Young and Peoples 2013). Examples include the Royal Society of Chemistry's 'Green Chemistry', the American Chemical Society's 'Sustainable Chemistry and Engineering', VCH-Wiley´s 'ChemSusChem` and Elsevier's 'Sustainable Chemistry and Pharmacy' and 'Current Opinion in Green and Sustainable Chemistry. Some of these journals have been publishing papers or editing special issues on GSCE to reach a wider and influential audience, mostly in the last few years (Eilks and Zuin 2018). Additionally a lot of chemistry related content is published in general journal on sustainability, e.g. the journal Sustainability published by MDPI.

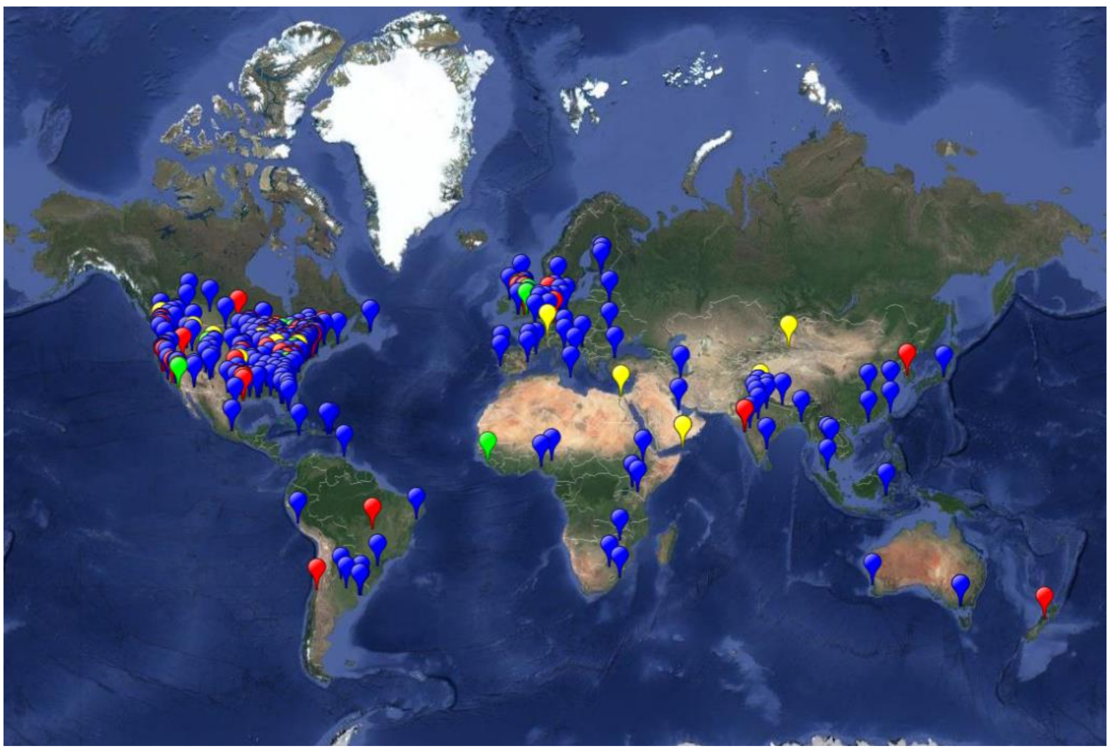
The concept of green - more than sustainable - chemistry has also been integrated in curricula of universities, as research programmes, courses and master's programmes. Green chemistry is, however, also implemented in regular courses[1]. Based on an initiative of the Federal Environmental Foundation in

[1] Universities offering courses on green chemistry include, for instance the Yale University (USA), University of Oregon (USA), University of Massachusetts, Lowell (USA), Yale University (USA), University of York (UK), University of Bath (UK), Queen´s University (UK), University of Nottingham (UK), University of Valencia (Spain), Universidad de Cordoba (Spain), University of Venice (Italy), Universities of Porto and NOVA Lisbon (Portugal), University of Amsterdam (The Netherlands), Ghent University (Belgium), McGill University (Canada), University of Toronto (Canada), King's University College (Canada), Queen´s University (Canada), Monash University (Australia), Federal

Germany (Deutsche Bundesstiftung Umwelt), a whole laboratory course was developed to teach organic chemistry practically based on ideas of green and sustainable chemistry. This lab-course, today, is available in more than ten languages (NOP n.d.) (see Figure 1.1).

Most of these initiatives were initially located in developed countries (e.g., Gross 2013; Juntunen and Aksela 2014; Kennedy 2016). Nevertheless, there are still a lot of things to do (Kitchens et al. 2006; Hamidah et al. 2017). Anyhow, an increasing number is emerging in developing countries and countries with economies in transition (e.g. Karpudewan, Ismail and Roth 2012b; Mammino 2018) or former communist countries (Lokteva 2018), covering all regions (see Figure 2.1). One of the fastest developments seems to be taking place in China (Wang, Li and He 2018).

Figure 2.1: Map of the Green Chemistry community conducting GSCE from educational, industry, government and non-government institutions (Oregon 2018).



The number of papers addressing GSCE has been growing in recent years. From more than 300 papers are available in the web of science since 1998, most address the development of curricular activities and experiments (e.g. Van Arnum 2005; Timmer et al. 2018), assessing student learning and attitudinal outcomes from these curricula (e.g. Karpudewan, Ismail and Roth 2012b; Mandler, Mamlok-Naaman, Blonder, Yayon and Hofstein 2012), the use of multidimensional green chemistry metrics (e.g. Eissen 2012;

University of São Carlos (Brazil), Federal University of Rio de Janeiro (Brazil), National University of La Plata (Argentina), Universidad Autónoma de Nuevo León (Mexico), Lomonosov Moscow State University (Russia), Mendeleyev University of Chemical Technology (Russia), University of Dodoma (Tanzania), University of Cape Town (South Africa), University of Delhi (India), Nankai University (China), City University of Hong Kong (China), Fudan University (China) among many others, some also in partnership with the private sector.

Dicks 2018) and integrating broader societal factors and new pedagogical approaches (e.g. Burmeister and Eilks 2012; Zowada, Gulacar and Eilks 2018; Holme and Hutchison 2018). A significant share of the papers has been published by scholars from developing countries or countries with economies in transition, such as Brazil, China, India, Malaysia and Mexico (see Figures 2.2 and 2.3).

Figure 2.2: Number of papers published on GSCE (ISIS Web of Knowledge; 1998-July 2018; topics: green chemistry education or sustainable chemistry education)

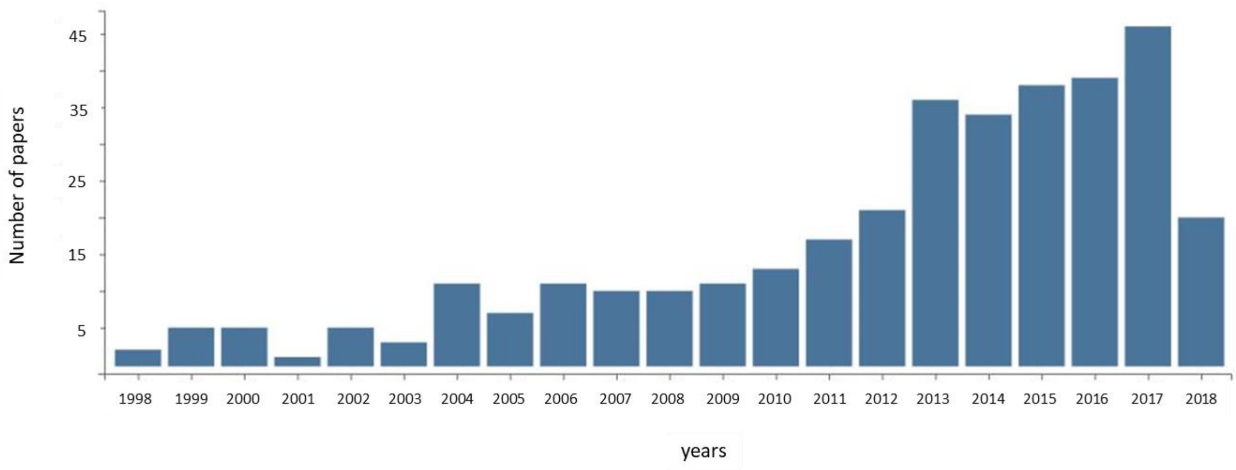


Figure 2.3: Countries of origin of papers published on GSCE (ISIS Web of Knowledge; 1998-July 2018; topics: green chemistry education or sustainable chemistry education).

Diverse approaches and ongoing reforms on green and sustainable chemistry education

Green and sustainable chemistry education has been taught differently depending on the institutional context, with a number of diverse approaches, materials and focus (e.g., Andraos and Dicks 2012). Based on a broad review of the literature, Burmeister, Rauch and Eilks (2012) outline four basic modes how GSCE can be implemented in the educational context of chemistry education. They suggest:

- Adopting Green Chemistry principles to the practice of science education lab work: it is suggested to apply the technical suggestion of green chemistry by Anastas and Warner (1998) to the handling of chemicals and laboratory work in chemistry education. Experiments are changed from macro- to the micro-scale, dangerous substances are replaced by less poisonous alternatives, and catalysts are used to stimulate reactions. The potential of this approach can be expanded, if students are asked to compare and reflect upon the altered strategies. One of the strength of this approach is that chemistry education contributes to sustainability by reducing the amounts of chemicals used and by producing less waste. The weakness of the approach is that it is often less embedded into continuous self-reflection upon how society handles debates around altered technologies. In this case, students will not develop skills for contributing to society's decision-making on new or alternative technologies. Additionally, students will barely touch upon the controversial nature of developments in society and the real interplay between science, technology and society.
- Adding GSC knowledge as content to chemistry education: strategies and efforts used in GSC become content in the chemistry curriculum. Basic principles behind GSC and their industrial applications are handled in chemistry classes, e.g. development of efficient processes in energy and raw materials conservation, structure, properties and application of innovative catalysts, and the chemical considerations behind the production of fuels stemming from renewable resources. The strength of this approach is that it highlights the learning of the chemical principles disguised behind modern processes and end products, thus making them meaningful to students.
- Using controversial socio-scientific issues from sustainability challenges which drive chemistry education: this approach integrates chemistry learning with socio-scientific issues (SSI) including current societal debate behind them. Lessons promote ESD by developing general educational skills in the area of an individual's actions as a responsible member of society. This approach differs from the second in that it includes both the chemical basis of knowledge and reflecting society's debate about its application in technology as factors to be learned. This approach not only focuses the learning of chemistry, but also the learning about chemistry as it is dealt with in society. The aspects of understanding societal debates and developing appropriate skills to actively participate in them are systematically included in the lesson. Students learn how to take part in societal decision-making in order to contribute to shaping a sustainable future. The strength of this approach is that it is skill-oriented with a sharp focus on ESD, relevant for both the future scientist and engineer and those who do not embark in a career in science and engineering.
- Chemistry education as a part of ESD-driven development of educational institutions and society: the fourth approach integrates chemistry learning with ESD-driven development of a whole educational institution and the society. This model suggests that school or university life and teaching becomes part of sustainable development. Educating children and students to become active citizens who have the ability and wish to achieve sustainable lifestyles requires entire process models. All shareholders in the institutions are required to explore future challenges, to clarify values, and to reflect on both learning and actively taking part in society in the light of sustainable development. Chemistry teaching should help contribute to such an altered culture

and can actively help to saving resources (energy, clean water, etc.) in the local environments, e.g. by service learning. It can offer suggestions for treating waste in an efficient fashion suitable for later recycling and life morph with life into an action-based pattern of living and learning.

Such pedagogical modes associated with a broader and systemic perspectives on SC, especially related to the last mode, have impact on behaviour patterns within a variety of communities, e.g., progressive greening and sustainability of universities, companies, and informal educational institutions (Mammino 2015; Zuin 2016; Kümmerer, Dionysiou, Olsson and Fatta-Kassinos 2018). For Kümmerer and collaborators, although examples of more benign chemicals exist, going beyond individual applications requires improved knowledge and management of the substance, material, and product flows in the global economy. Knowledge of the local, regional, national, and global variations and dynamics of these flows would help to identify opportunities and levers for reducing their chemical complexity. Better knowledge of products, their targeted design, and an enhanced understanding of the function they offer are keys for achieving this goal, which should be also a matter of study in initial and continuous professional education.

In practice, all four of the above-mentioned approaches may overlap or even being combined in order to focus on sustainability and GSCE. It needs however to be said that McKeown (2006) suggests that pure learning about sustainable development will not contribute to ESD: "An important distinction is the difference between education about sustainable development and education for sustainable development. The first is an awareness lesson or theoretical discussion. The second is the use of education as a tool to achieve sustainability. In our opinion, more than a theoretical discussion is needed at this critical juncture in time. While some people argue that 'for' indicates indoctrination, we think 'for' indicates a purpose. All education serves a purpose or society would not invest in it."

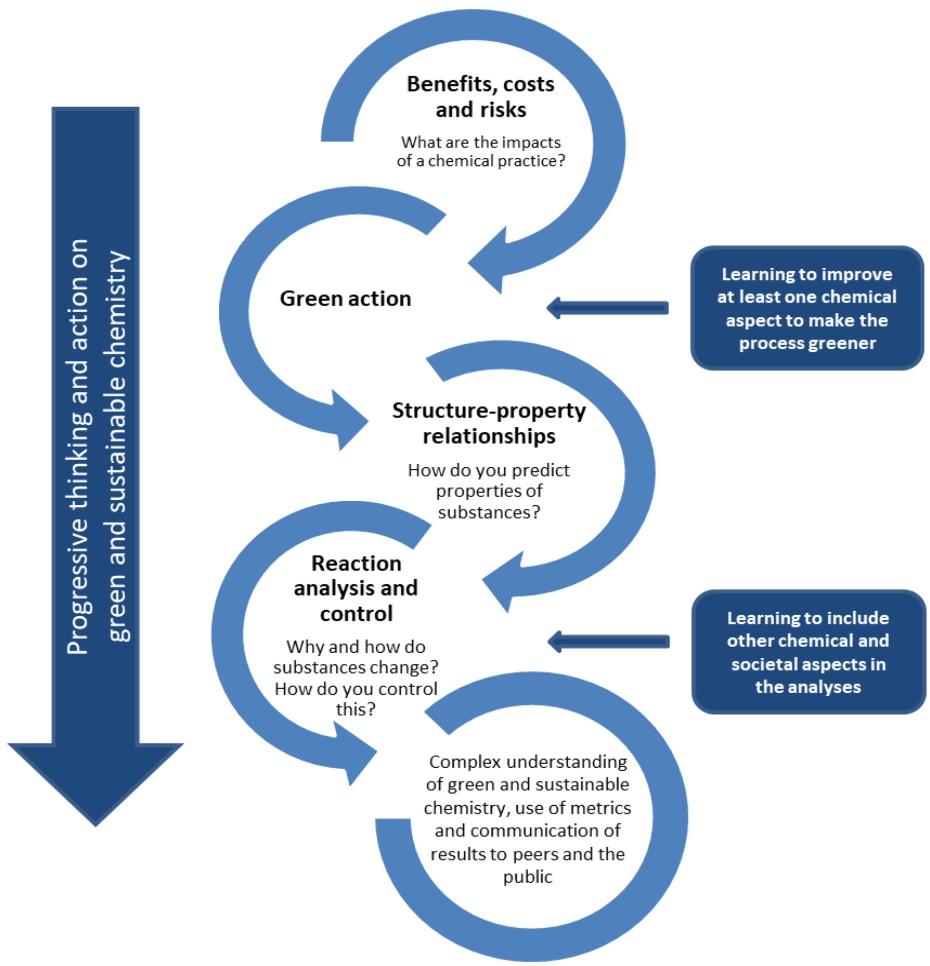
Box 2.1: Green chemistry and sustainability in professional education and training courses: a case study from Brazil

Organised and run by industrial entrepreneurs - through the National Confederation of Industry and through the state federations - the National Service of Industrial Training (SENAI) was created to train qualified workers for Brazilian industry. Together with Brazil's Ministry of External Relations, it operates in Cape Verde, Guinea-Bissau, Guatemala, Paraguay East Timor, Mozambique, Peru, Jamaica, São Tomé and Príncipe. In 2015, the SENAI Green Chemistry Institute Brazil was launched, and has been committed to increase the general global awareness, and capacities on deployable Green Chemistry approaches aiming at the designing of products and processes that advance global environmental benefits throughout their life cycles. Under the umbrella of UNIDO's Green Chemistry Initiative, a pilot project will be implemented, demonstrating that Green Chemistry works for applications at large scale in the area of bio-based plastics production in Brazil. In addition, other case studies shall be identified that have an impact on advancing green chemistry and green engineering technology applications in developing countries and transition economies (GEF n.d.).

A variety of educational materials has been developed to convey the principles of green and sustainable chemistry in school chemistry education and the academia, collections are provided, e.g., by Eilks and Rauch (2012), Eilks and Zuin (2018), Levy and Middlecamp (2015) and Zuin and Mammino (2015). If the term ‘green chemistry’ is put into the Education Resources Information Center database (ERIC n.d.), 126 hits to peer-reviewed articles were identified (by January, 2019) with 41 out of the first 50 referring to articles published in the *Journal of Chemical Education* published by the ACS. Thus, as an example, a search in the *Journal of Chemical Education* for ‘green chemistry’, as the most known journal in chemistry education, provided 623 hits to any related resources in the journal (by January, 2019). Expanded to the ACS publications database and combined with ‘education’ 2833 hits were found. The identified resources present a whole range of information, from news, announcements and awards on the one side, but also overviews on new courses on green and sustainable chemistry, examples for teaching activities, and numerous green chemistry laboratory demonstrations and suggestions for practical work on the other.

The general aim of GSCE is to prepare future chemists to develop new products and processes based in GSC and innovation for a sustainable future (Warner 2016; Mahaffy *et al.* 2018). Given an increasing consideration for all three dimensions of sustainable development, academics have responded by adjusting course contents and materials to adequately consider societal factors of sustainability (e.g. Armstrong *et al.* 2018; Burmeister and Eilks 2012). The case has been made for a re-conceptualisation of GSCE by adjusting curricula and methodologies to “foster eco-reflexive chemical thinking and action” (Sjöström, Eilks and Zuin 2016; Sjöström and Talanquer 2018). Integrating this dimension into chemistry education at all educational levels should aim on enabling individuals to respond to complex challenges in line with the principles of sustainable development (Figure 2.4), both if they major in science or not, in a systemic and holistic pedagogical perspective.

Figure 2.4: Steps to promote GSCE (Adapted from Armstrong *et al.* ,2018, Sjöström and Talanquer 2018).



The great potential of existing green and sustainable chemistry education networks

Strengthening transnational collective multi-sector efforts towards a common agenda for GSCE promoted by adequate pedagogical approaches requires the engagement of existing national, regional and international networks, aggregating champions and innovators in this field (Collins, 2001, Yale University n.d.).

Many national chemical societies founded sections, committees or networks for green or sustainable chemistry, e.g., the German Chemical Society (GDCh), the Royal Society of Chemistry (RSC) or the ACS, being the last one responsible for the creation of a roadmap for undergraduate green chemistry education together with a wide range of stakeholders, such as its own members involved in chemistry education, non-profit educational organisations, universities that have changed their curricula in some extent as well as industry leaders. Also, the International Union for Pure and Applied Chemistry (IUPAC) formed an interdivisional committee on green chemistry for sustainable development (ICGCSD) in 2017, superseding the former sub-committee on Green Chemistry. In common, all of these organisations are discussing principles, directives and practices on GSC, but also how to better implement it into education.

Other global networks have been established to advance the mainstreaming of GSCE involving both developed and developing countries, for example the European platform Suschem (n.d.) launched in 2004, the Green Chemistry & Commerce Council (GC3 n.d.) originated in 2005 and the Global Network of Chemistry Centres (G2C2, n.d.), created in 2013. More recently, the International Sustainable Chemistry Collaborative Centre (ISC3) located in Germany was launched in 2017. The ISC3 (n.d.) is a global institution, multi-stakeholder platform and think tank, managing a multi-purpose knowledge platform and a network of experts on GSC which also offers training and support for implementation, especially for developing countries, and carries out innovation scouting activities to discover new technologies, processes and business models, with emphasis on educational processes.

This centre has one special hub addressed to Research & Education, allocated at the Institute of Sustainable and Environmental Chemistry, Faculty of Sustainability of the public Leuphana University of Lüneburg. The key features of its activities are interdisciplinary and openness, related to stakeholders, research topics, ideas, concepts and an extensive understanding of sustainable chemistry encompassing and beyond GC, which is an important building block of sustainable chemistry. As such it focuses on developing and advancing a better understanding of the opportunities and possible pitfalls of sustainable chemistry, putting on emerging concepts and hot topics of research on GSC by doing own research, collecting and assessing good examples of GSC as well publishing related studies.

Overall, for all these global GSC initiatives, strategic partnerships and the establishment of networks of educators have been identified as a key determinant for success (Haack and Hutchison 2016; Zuin 2016).

3. Overcoming barriers: key determinants for effective educational reform

Implementing green and sustainable chemistry education

Making current chemistry practice green and sustainable and divulging it widely is a relatively new concept for some countries, especially important to developing ones. In those countries, current curricula for chemists' and engineers' education barely consider or can implement environmental sustainability as part of its courses and learning objectives. This makes it difficult to educate human resources to have consciousness and act adequately considering the implications of synthesising chemicals with multiple applications, while taking into account the life cycle of the chemical and its final fate in the environment (Barra and Gonzalez 2018). Generally, more consciousness is needed for educating future chemists in both, doing GSC but also assessing impacts of chemicals by operating corresponding metrics (e.g. McElroy, Constantinou, Jones, Summerton and Clark 2015) and learning about them (Eissen 2012; Dicks 2018). The life-cycle assessment of chemicals can be made subject to learning chemistry (Juntunen and Aksela 2013a) with potential positive effects on student attitudes towards chemistry learning (Juntunen and Aksela 2013b).

Currently, a number of countries face several challenges regarding the design and implementation of GSCE where there is a lack of scientists considering corresponding approaches. This acts as a barrier to awareness-raising of new professionals and scientists sensitised to addressing the issue. Other aspect is the limited number of pedagogical material produced by accredited institutions, with adequate educational standards, as the RSC, ACS and Springer's books on this topic. The language barrier and limited access to the international literature might be further hurdles for implementation of GSCE in certain countries. To date, few universities are pro-actively addressing the issue. Current curricula for chemists and engineers in many universities provide limited room for green chemistry principles and practices, and sustainability issues. For instance, there is thus a need to strengthen education in chemical synthesis and green chemistry principles to address molecular design and minimize impacts *ab initio*, in addition to a pursuit of material innovation, including online pedagogical platforms and virtual activities (Haley *et al.* 2018).

In fact, active and online learning has been used inside and outside of an academic setting (Summerton et al. 2018). As it is flexible enough to be compatible with learners in full time employment who may have restrictions on their time commitments, online learning is a tool that can be readily adopted within industry both for initial and continuing professional development purposes. Online active learning should incorporates elements of interactivity or other methodologies that encourage more in-depth interaction with the material therein other than simply reading or viewing it.

For instance, an online GSC learning module available in the *moodle* platform at the Federal University of São Carlos, Brazil (n.d.), for initial teacher education focusing on local and global cases studies was designed not only for Latin American and African universities, with the support of IUPAC (n.d.). Using this learning active approach, the students were experientially participating in the learning process, which enabled them to engage in higher order cognitive tasks such as critically 'analysing' and 'evaluating', with a deeper understanding of the subject matter, as were the cases of the topics selected by the students (bio-pesticides for sustainable agriculture, biorational control of insects, use of agro-industrial waste to obtain high-value chemicals, among others, IUPAC, n.d.).

Regarding continuing professional development, the CHEM21 (n.d.) online platform established by the EU IMI CHEM21 project (Chemical Manufacturing Methods for the 21st Century Chemical Industries) was designed to provide a broad range of free, shareable and interactive educational and training materials to promote the uptake of green and sustainable methodologies in the synthesis of pharmaceuticals. Interactive elements include multiple choice quizzes with instant feedback, and downloadable problem-solving exercises (that can be carried out individually or in groups in a workshop setting) to encourage critical thinking on topics such as metrics, solvent selection and process safety (Summerton, Hurst and Clark 2018; Figure 3.1).

Increased demand from the private sector for a new generation of chemists

Embedding GSC in academic and professional education across supply chains can contribute to building a community with a strong understanding of the nexus between chemistry, product design and sustainability (GreenCentre Canada n.d.). Many initiatives prioritise education of teachers and lecturers since they can influence the knowledge and opinions of present and future generations (Karpudewan, Ismail and Roth 2012a; GC3 n.d.; Beyond Benign n.d.). Mainstreaming GSCE not only at chemistry and engineering departments, but also in business and law schools, public administration and companies is critical given these stakeholders' role in setting or assessing and implementing technological, economic, financial and fiscal activities and policies. Here it is important that chemists accept their crucial role in informing the public debate about current trends and challenges associated to the ever changing world of chemistry towards GSC (Eilks, Sjöström and Zuin 2017).

Figure 3.1: CHEM21online learning platform (n.d.)

Some professional education programmes geared towards green management have been described, showing that employee attitudes to green management approaches became more positive and motivated in terms of participating in new green management activities including education programmes for other partners (Lee 2016; Oregon 2018).

Overcoming professional and institutional resistance

Warner (2015) clearly outlined that organisations and societies which start early towards implementing GSC and GSCE will have a significant competitive advantage in times of change. Nevertheless, the barriers to successfully implementing GSCE are significant and quite similar globally. Cultural and institutional openness to change, or professional conservatism, have been identified as critical obstacles (Vallee 2016). According to Matus *et al.* (2012), corroborated by recent research conducted with leaders from several sectors worldwide (2018), there is a complex set of interconnected issues acting as barriers to the effective implementation of GSCE and wider sustainability considerations. Most fall into the categories of inertia and resistance related to organisational and cultural *status quo*; insufficient financial, social and economic support; and a lack of knowledge about GSC among staff. Another challenge identified in the literature is the absence of harmonised and clear definitions and metrics used by academia and decision makers (Matus *et al.* 2012).

Despite these challenges, a number of opportunities exist. As outlined by Matus *et al.* (2007) and De Soete *et al.* (2017), a number of stake-holders, including industry, academia, NGOs and policy-makers can make an important contribution by facilitating a shift from a focus on exposure control to hazard reduction, also emphasising that low risk evaluations require both hazard and exposure data analysis in order to ensure that chemicals are safe for their intended use. A number of local case studies have demonstrated the successful integration of GSC, including in the private sector. Several strategies including distance learning with both blended and face-to-face approaches have shown a range of opportunities to overcome identified gaps, including transdisciplinary research and teaching, industry 4.0 and Big Data systems (Zuin and Mammino 2015; Ellen MacArthur Foundation n.d.). Moreover, tools have been developed to assist universities in assessing how their curricula address sustainable development as a means of identifying opportunities for reform to capture sustainability issues in a more strategic manner (Lozano and Watson 2013).

The need to bring together policy-makers, scientists and the private sector

Public support for GSC requires a broader societal education, in which stakeholders should be considered, including chemical producers, entrepreneurs, environmental justice groups, NGOs, downstream businesses, consumers, labour and professional associations. While motivated educators are necessary for the curriculum-greening process, they are not enough. It has been observed that this process can be significantly influenced by other constituents that can support them, providing resources such as educational materials, case studies etc. (Centi and Perathoner 2009; Vallee 2016). For example, the ACS has been divulging tools to support work carried out in teaching laboratories, additional curricular materials for teachers, local government resources, and links to online networks, essentially for the USA. More recently, a new initiative to screen, assess, develop and apply international study programmes of sustainable chemistry education has been launched (ISC3 n.d.). The ISC3-Research Hub aims at offering scientific courses on a global level involving, e.g., universities and authorities especially from developing countries and economies in transition, in order to promote correlated programmes in their institutions.

4. Options for action

- Standardise and use of key concepts such as green and sustainable chemistry as well as green and sustainable chemistry education
- Develop appropriate local and global programmes for GSCE, define fundamental pedagogical contents, objectives, methods and evaluation processes
- Gather and disseminate best practices in integrating GSCE in chemistry and other curricula at secondary, higher (university) and technical educational levels
- Scale up the education on GSCE of teachers and lecturer across all education levels
- Enhance funding and cooperation, including via existing GSC networks to further promote and implement GSCE in developed, developing and transition economies
- Embed GSC as a critical element of wider efforts to transform education, including through strategic collaboration with programmes, such as the UNESCO Education for Sustainable Development initiatives
- Engage local and global stakeholders, including the private sector, academia and civil society in the development and implementation of effective strategies of GCSE in order to prepare students to address global challenges of sustainability
- Further mainstream GSCE in professional education, including via public-private partnerships

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