UN environment programme

Specialized Manual on Green and Sustainable Chemistry Education and Learning

Advancing Green and Sustainable Chemistry Education and Learning in All Segments of Society

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Email: science.chemicals@un.org
Website: https://www.unenvironment.org/explore-topics/chemicals-waste

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About this Specialized Manual

This Specialised Manual on Green and Sustainable Chemistry Education responds to resolution 4/8 adopted at the fourth United Nations Environment Assembly (UNEA-4) which requested the United Nations Environment Program (UNEP) to develop manuals on green and sustainable chemistry. This Specialized Manual closely relates to, and expands upon UNEP's Green and Sustainable Chemistry: Framework Manual (UNEP 2020) by focusing on the topic of education and learning to advance green and sustainable chemistry. The Framework Manual was welcomed and its use was encouraged in resolution 5-7 adopted at UNEA-5.2

Since not all readers may have read the Framework Manual, chapter 1 of this manual introduces the global context, including global trends related to chemistry, as well as the framework manual, and its 10 green and sustainable chemistry objectives and guiding considerations. Starting from chapter 2, the contents of the Specialized Manual focus on green and sustainable chemistry education and learning. Topics covered include: the rationale for scaling up green and chemistry education (Chapter 2); key action steps and considerations for effective green and sustainable chemistry education and learning (Chapter 3); green and sustainable chemistry in formal, non-formal and informal education (Chapters 4 and 5). The final chapter (Chapter 6) features guidance on strategic action and road maps for green and sustainable chemistry education.

Who are the actors and change agents targeted by this Manual?

This Specialized Manual on green and sustainable chemistry education seeks to inspire change agents engaged in, or influential in shaping and transforming education and learning programmes concerned with chemistry and sustainablity. They include, but are not limited to:

- Governmental officials responsible for developing education policies and curricula as well as those involved in the development of chemical management policies.
- Senior and mid-level managers in companies engaged in chemistry and product innovation.
- Leaders and staff in non-governmental organizations or media, engaged in chemistry and sustainability learning (e.g. environmental NGOs, worker organizations, consumer groups).
- Educators, teachers and administrators in primary, secondary and university education engaged in delivering science and chemistry education programmes.
- Other professionals in fields which stand to benefit from implementing green and sustainable chemistry practices.

By providing practical guidance for designing effective green and chemistry learning, and featuring examples and resources, the manual intends to stimulate and facilitate transformative changes through education to reap the full potential of green and sustainable chemistry.

ADVANCING GREEN AND SUSTAINABLE CHEMISTRY - **THE NEED FOR EDUCATION**

1

The first chapter of the specialized education manual calls attention to the need for a transformation to green and sustainable chemistry and refers to the critical role of education. Key components from UNEP reports, the Global Chemicals Outlook II (GCO-II) and the Green and Sustainable Chemistry: Framework Manual, are included to support the rationale for shifting chemistry practices through learning. The objectives, structure and target audience of the specialized manual are presented in this chapter.

Key Chapter Takeaways:

- The world faces a triple planetary crises (climate change, biodiversity loss and pollution) and green and sustainable chemistry is a critical tool to address them.
- A transformation to green and sustainable chemistry will require actions to advance education and learning reform.
- Current chemistry education suffers from lack of context and omission of important sustainability-related topics.

1.1 A transition to green and sustainable chemistry is urgent and education is key

In a globalized world, the needs and demands of a growing population and megatrends, (e.g. urbanization and the growing global middle class) shape the production, trade and consumption of products and services for which chemicals are used in significant quantities. As a result, the number of chemicals is ever increasing. Hazardous chemicals and other pollutants continue to be released and disposed of in large quantities, affecting individuals and communities worldwide. Synthetic chemicals are now ubiquitous in humans and the environment and chemical pollution has become a major cause of human disease and premature death. The World Health Organization (WHO) estimates the burden of disease from selected chemicals was 2 million lives and 53 million disability-adjusted life years (DALYs) in 2019 (WHO 2021). Gender-specific impacts from chemical exposure due to differing physiological susceptibility and social contexts are also concerning. Examples include adverse effects on male fertility or on fetal development (UNEP 2023).

Along with the concerning global pollution situation, the world faces two additional crises in climate change and biodiversity loss. Green and sustainable chemistry can be a tool to address this triple planetary crises. Innovations in chemistry and advanced materials have created opportunities throughout the value chain which can contribute to solving a range of sustainability challenges. Examples include energy storage technologies, sustainable building materials, circular products and renewable feedstocks. Developing, scaling-up and implementing these innovations will require not only a new generation of chemistry professionals, but also workers, policymakers and citizens with an awareness and understanding of green and sustainable chemistry.

Figure 1-1 **GCO-II Cover**

1.2 UNEA Mandate to develop green and sustainable chemistry manuals

Resolution 4/8 on the Sound Management of Chemicals and Waste adopted by the United Nations Environment Assembly at its fourth session (UNEA-4) in 2019 recognized the value of developing a better understanding of sustainable chemistry opportunities globally. The resolution requested the Executive Director to synthetize UNEP's analysis of best practices in sustainable chemistry into manuals on green and sustainable chemistry, in consultation with relevant stakeholders. It also requested to continue the work on a holistic approach for the sound management of chemicals and waste in the long term, taking into account both the importance of the sound management of chemicals and the potential benefits of chemicals for sustainable development.

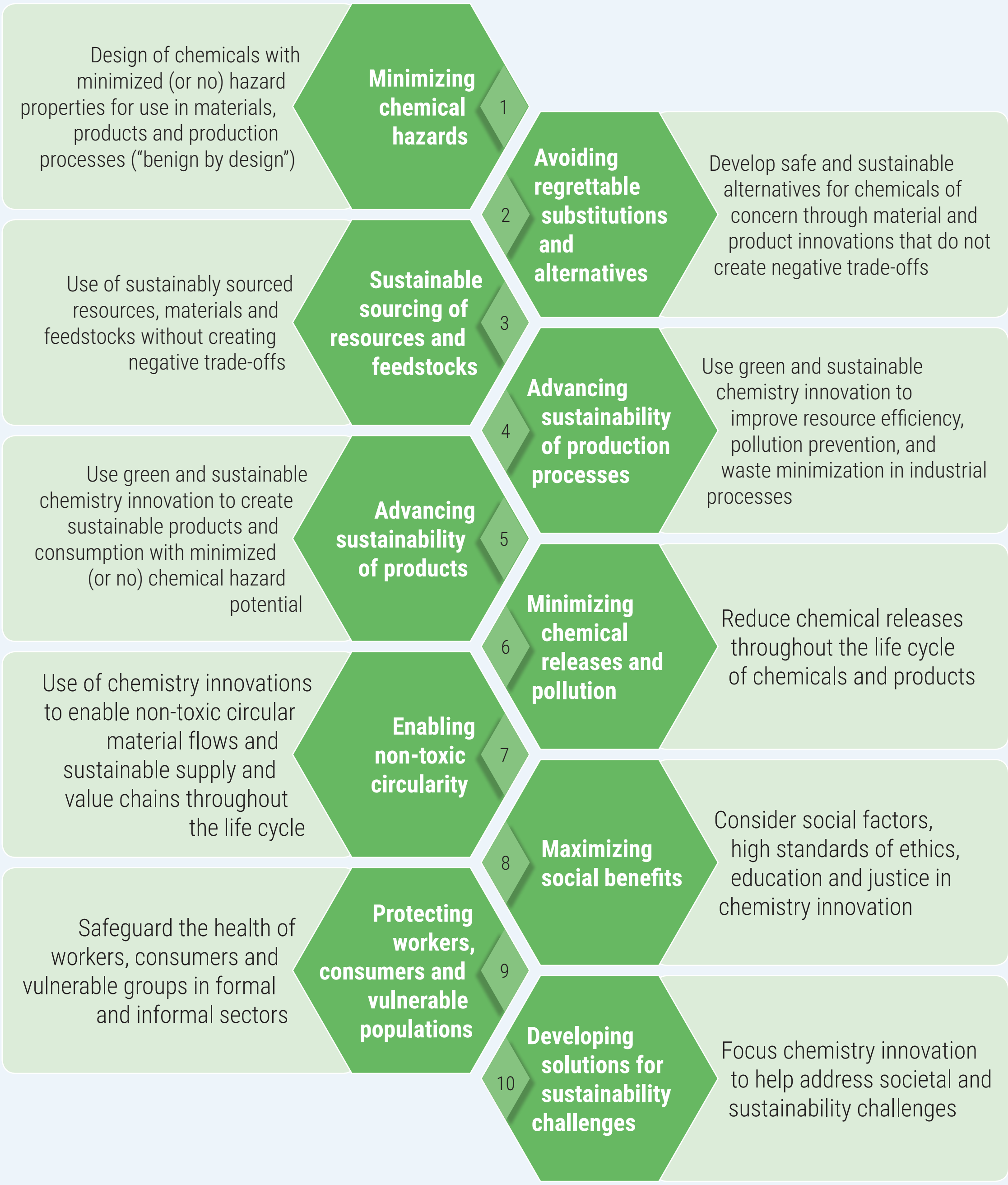
Responding to the UNEA Resolution, UNEP's Green and Sustainable Chemistry: Framework Manual (UNEP 2020) introduces various facets of green and sustainable chemistry with the intention to foster general learning, reflection and scaling-up action based on a common global understanding of the concept. It features an organizing framework that unpacks various topics relevant in green and sustainable chemistry literature and presents 10 green and sustainable chemistry objectives and guiding considerations (UNEP's Objectives) to guide innovation and help assess current practices.

UNEP's Objectives are offered to stakeholders to stimulate action at various levels and in different settings, including through education programmes and initiatives. The objectives range from eliminating (or minimizing) chemical hazards, to ensuring that chemistry innovations address global sustainability challenges. The assumption is that if innovations become compatible with UNEP's Objectives, the potential of chemistry to implement the 2030 Sustainable Development Agenda can be fully reaped.

Figure 1-2 Cover of UNEP's Green and Sustainable Chemistry: Framework Manual

Box 1-1 UNEP's 10 Objectives and Guiding Considerations for Green and Sustainable Chemistry

The 10 green and sustainable chemistry objectives featured in chapter 3 of the UNEP Green and Sustainable Chemistry Framework Manual (UNEP 2020) provide a reference framework for researchers, policymakers and other stakeholders on how chemistry can be compatible with and support the 2030 sustainable development agenda. UNEP's Objectives take into account the widely known principles of green chemistry and are complemented by broader sustainability considerations.



1.3 Specialized Manual on Green and Sustainable Chemistry Education and Learning

The transformation to a chemistry that is greener and more sustainable requires awareness, engagement and action by a wide range of individuals, from scientists and corporate managers, to policymakers and citizens. Achieving this shift also requires supportive and effective education institutions and increased public awareness that can leverage the needed change.

While many promising developments have taken place in the domain of green and sustainable chemistry education, much remains to be done, including in developing countries and transitioning economies. It is for this reason that UNEP, with the support of an international expert group, decided to dedicate the first specialized manual to the topic of green and sustainable chemistry education and learning.

This Manual addresses both educators and strategic change agents (see Box 1-2). Ultimately, the action carried out by these actors raises the awareness, enhances knowledge and develops the skills of a diverse group of individuals who directly (as research scientists), or indirectly (as enabling actors such as policymakers or consumers) play a role in accelerating a transition to green and sustainable chemistry.

The specific objectives of the Specialized Manual are to:

- Convey the importance of strengthening education to advance green and sustainable chemistry.
- Provide a succinct synthesis of the diverse dimensions of green and sustainable chemistry learning.
- Provide guidance to educators and other change agents.
- Provide examples and resources for different education levels and settings
- Promote and guide strategic planning for green and sustainable chemistry education.

Box 1-2 Inspiring action of educators and strategic change agents

The education system (in broad terms) includes a diverse set of institutions and actors who all have roles in fostering transformative changes in education for green and sustainable chemistry. This Specialized Manual targets all of these groups.

Strategic change agents include, for example:

- rectors, deans and heads of departments at universities engaged in science teaching and innovation;
- senior policymakers in government responsible for designing and approving curriculum in education institutions; or government officials which lead the development of professional training requirements
- CEOs or heads of department of companies from across the value chain, who support professional development of staff.

At the operational level, **educators and teachers** are more directly engaged. They design and deliver learning programs and interventions, from primary school science teaching or specialized university courses, to awareness raising campaigns run by NGOs.

1.4 Limitations in past chemistry: The result of gaps in learning and education

Chemistry is the science from which all materials are created and has resulted in positive impacts on the lives of many people. Despite the numerous ground-breaking innovations, the chemistry field has faced many challenges. A fundamental issue has been the lack of awareness and knowledge with respect to life cycle thinking when developing new chemicals and products. Many cases are now well documented in which an innovation was celebrated at the time of invention only to discover adverse environmental and human health impacts years later. A well-known example is the case of Chlorofluorocarbons (CFCs), whose detrimental impact on the earth's ozone layer was revealed decades after they had been widely incorporated into refrigerators and air conditioners as cooling agents. This example highlights the need to educate product designers and chemists to follow a life cycle approach, this is especially critical at the design stage.

These challenges can be traced back to the way chemistry is taught. Few chemists are trained to consider life cycle impacts of chemicals on human health and the environment when synthesizing new molecules. Closely related is the lack of toxicology and eco-toxicology considerations in chemistry curricula. In chemical engineering education, industrial process design learning is rarely accompanied by life cycle or global systems considerations (Byrne and Fitzpatrick 2009). These gaps are exemplified in educational chemistry laboratories where many hazardous chemicals continue to be used, and robust training in laboratory and chemical safety training is lacking (Aubrecht *et al.* 2019).

Furthermore, although the traditional approach of teaching science and chemistry has increased knowledge of the natural world and resulted in technological advances, it has not succeeded in addressing global challenges, such as pollution, climate change, poverty and other societal issues (Orgill, York and MacKellar 2019). This limitation has resulted in missed opportunities to stimulate research and innovation that addresses broader sustainability problems.

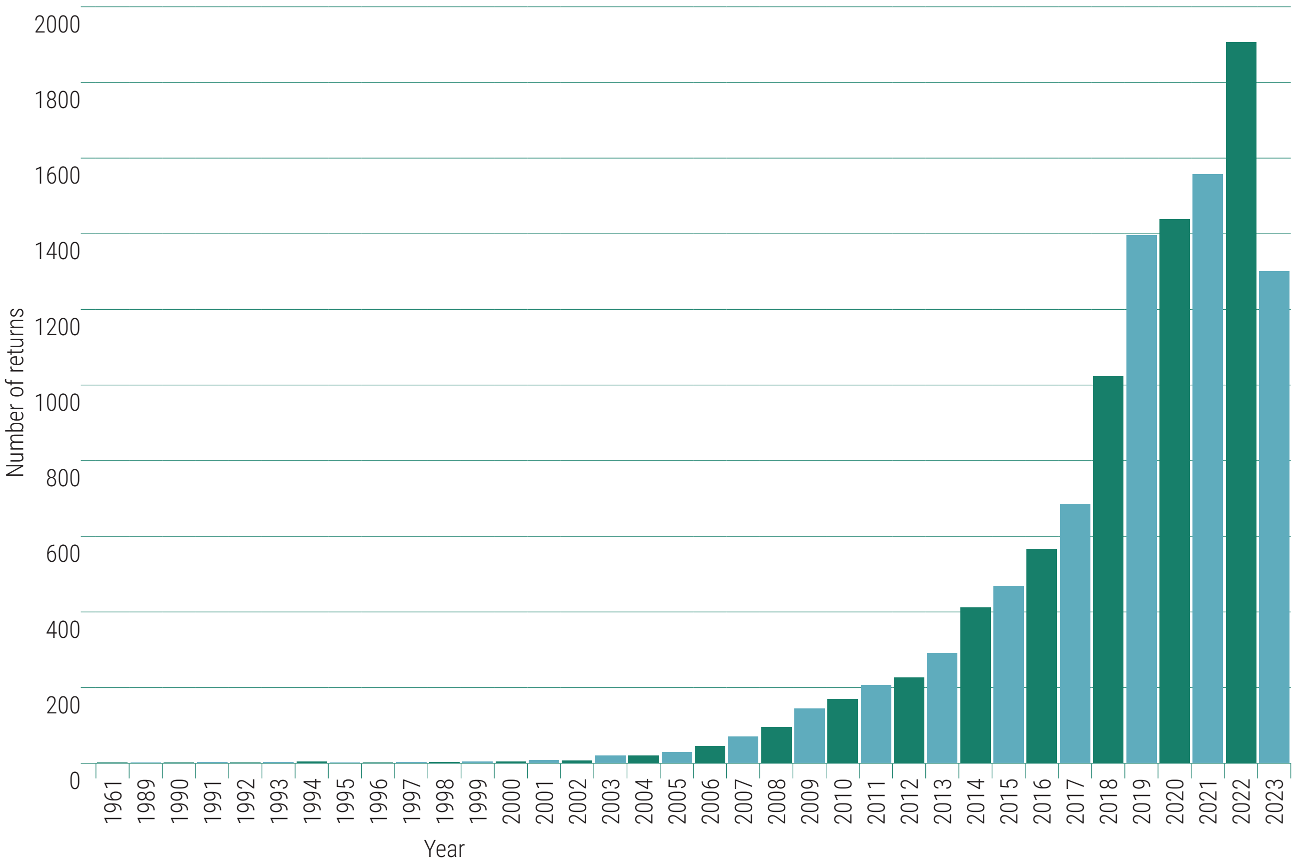
Box 1-3 Late lessons from early warnings: science, precaution, innovation (EEA 2013)

The 2013 flagship report of the European Environment Agency (EEA) "Late lessons from early warnings" presents examples of chemical and technological innovations that resulted in significant societal damage and costs. Using case studies, such as lead in petrol, Bisphenol A, vinyl chloride, and DDT, the report sheds light on the failure of the system to anticipate harm. It also discusses the role of key actors in ignoring early warnings and in manufacturing doubt about the science supporting such warnings. The report concludes that society can avoid making similar mistakes by taking a precautionary approach (EEA 2013). Using this approach can help to advance UNEP objective 1 "minimize chemical hazards".

1.5 The momentum for teaching green and sustainable chemistry education is growing

Driven by a growing imperative, increased societal interest to achieve sustainability, and a community of committed researchers and educators, the topic of green and sustainable chemistry education is gaining significant momentum. In an international survey conducted by Student's Organizing for Sustainability (SOS), 92% of respondents stated that sustainable development should be universally taught and promoted by universities (SOS 2020). Actors in the chemistry education field are striving to meet student's demand as is illustrated by the growing number of peer-reviewed publications on the topic of green and sustainable chemistry education (Figure 1-3). A particularly promising development is that some traditional textbooks in general and organic chemistry are starting to include green and sustainable chemistry considerations (Aubrecht *et al.* 2019).

Figure 1-3 Trends in green and sustainable chemistry education publications (Number of returns for "Green Chemistry Education" on PubMed) (Aubrecht *et al.* 2019)



KEY CONSIDERATIONS AND APPROACHES FOR GREEN AND SUSTAINABLE CHEMISTRY EDUCATION

2

In this chapter, important considerations, concepts and initatives are presented that are relevant to transforming chemistry education. Systems thinking is introduced as a key concept to move chemistry education towards sustainability. Additional frameworks such as learning using the UN Sustainable Development Goals (SDGs) and education for sustainable development (ESD) are discussed as vehicles to promote and guide green and sustainable chemistry learning. Finally, a call is made to engage audiences throughout society in green and sustainable chemistry learning, with the roles and needs of different target groups explained.

Key Chapter Takeaways:

- Systems-thinking prepares learners to address complex, global issues by showing how chemistry affects human health and the environment.

- Green and sustainable chemistry education can be inserted into broader sustainability education programs to extend its reach and raise awareness of its importance.

- All segments of society are important to target for green and sustainable chemistry education with each group having a clear role and specific learning needs.

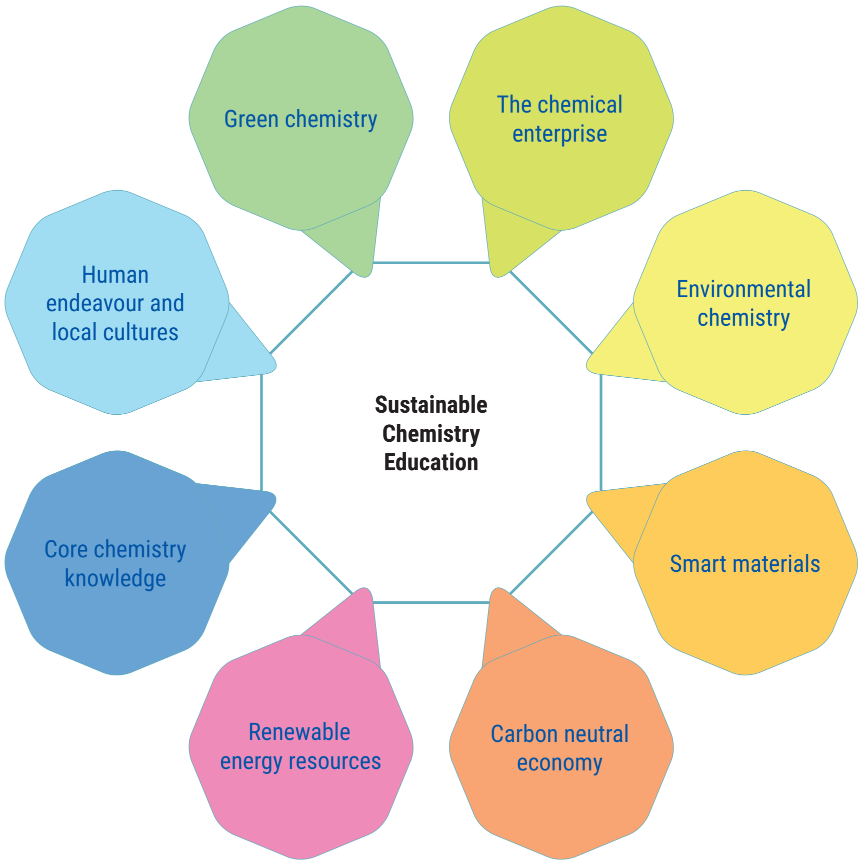
- Several topics which are central to green and sustainable chemistry are often ignored in traditional chemistry education, but resources and initiatives exist to support their inclusion.

2.1 Expanding chemistry education with systems thinking and sustainable development

Educators engaged in chemistry have started to advocate for the introduction of systems thinking to address some of the identified weaknesses in chemistry education. Systems thinking involves expanded thinking across spatial and temporal scales, as well as across disciplines, from molecular, to biological, to economic and social (Wiek, Withycombe and Redman 2011). Promoting systems thinking can support educators to teach chemistry as a science that benefits society while preparing learners to be aware of and tackle global challenges and sustainable development.

A systems-thinking approach in teaching green and sustainable chemistry therefore covers two

Figure 2-1 Selected systems dimensions of sustainable chemistry education (adapted from Hill, Kumar and Verma 2013, page 29)



Sustainable chemistry education complements traditional chemistry by covering topics, sectors and target audiences considered essential for chemistry to help achieve sustainable development objectives, including, but not limited to green chemistry.

important aspects of chemistry: the adverse effects many chemicals and chemical processes have on human and environmental health; and assessing the potential of chemistry to contribute to solving global challenges, such as those outlined in the UN SDGs. Resources to teach the 2030 Sustainable Development Agenda, systems thinking, and the role of chemistry to support its implementation are referred to later in this chapter in the learning topics section. An example of how Agenda 2030 and the SDGs have catalyzed learning and research for green and sustainable chemistry is the United Nations Education, Science and Culture Organization (UNESCO) programme, "Green Chemistry for Life". The programme supports research on novel technologies that address environmental and sustainability concerns. It provides research grants to young scientists to demonstrate their inventiveness. The grants cover green chemistry and allied areas in biochemistry, geochemistry, biotechnology, ecology and healthcare which provide input to sustainable development (UNESCO 2021).

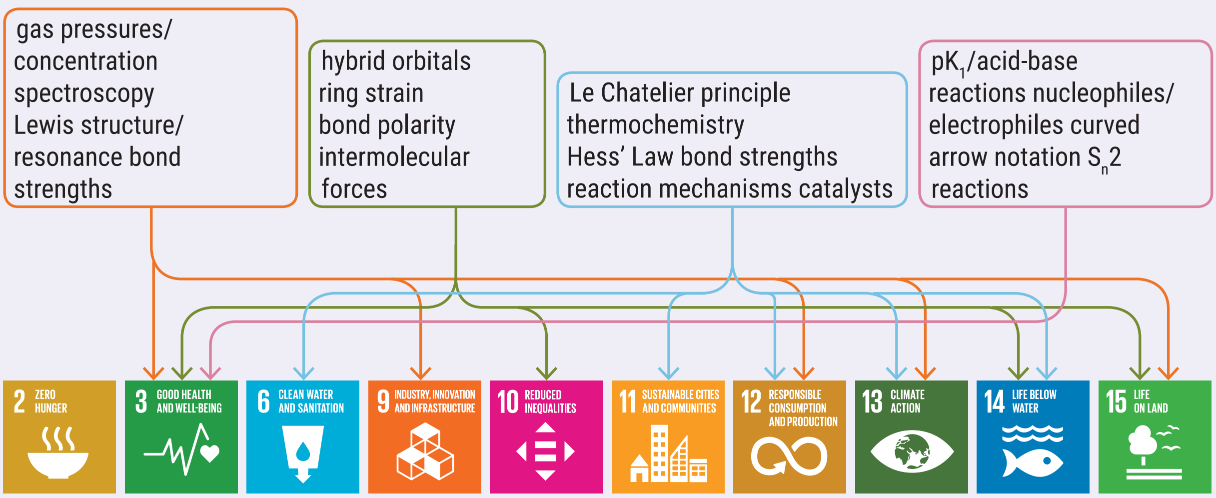
2.1.1 Creating linkages with Education for Sustainable Development (ESD)

Spearheaded globally by UNESCO, education for sustainable development (ESD) is crucial to enable the achievement of Agenda 2030, in particular for SDG 4. ESD originated from the need for education to address growing sustainability challenges, and include global issues, such as climate change and biodiversity, into teaching and learning. The concept embraces an action-oriented pedagogy for learners to develop awareness, knowledge and skills needed to take action on sustainable development (UNESCO 2019a).

Integrating green and sustainable chemistry considerations into ESD initiatives is important to reach the broader education community. One practical way to actively engage is through the "ESD for 2030" initiative. It is a global framework adopted by the 40th UNESCO General Conference and acknowledged by the 74th UN General Assembly in 2019. Under ESD 2030, UNESCO has developed a road map publication which

Box 2-1 United Nations Sustainable Development Goals as a Thematic Framework for an Introductory Chemistry Curriculum (Petillion, Freeman and McNeil 2019)

During a first-year chemistry course at the University of British Columbia in Canada, the UN SDGs were used as a thematic framework for instruction. The framework applied a systems thinking approach to explore the relevance of chemistry to societal and global challenges. Course concepts traditionally limited in their application to isolated textbook chapters, were applied to environmental and societal systems embodied by specific SDGs using in-class group activities. Learning outcomes and student attitudes were examined via a course-end survey. It revealed that for many students, the SDG-framed learning activities aided in their understanding of course concepts (Petillion, Freeman and McNeil 2019).



Box 2-2 Key SDGs for ESD

SDG 4: Quality Education and Lifelong Learning
Target 4-7. By 2030, ensure that all learners acquire the knowledge and skills needed to promote sustainable development, including, among others, through education for sustainable development and sustainable lifestyles, human rights, gender equality, promotion of a culture of peace and non-violence, global citizenship and appreciation of cultural diversity and of culture's contribution to sustainable development.

SDG 12: Sustainable Consumption and Production
Target 12.8. By 2030, ensure that people everywhere have the relevant information and awareness for sustainable development and lifestyles in harmony with nature.

encourages country initiatives to mainstream ESD in education and sustainable development. The initiative is supported by the "ESD for 2030 Network (ESD-Net)" which encourages leadership and action from Member States, and other stakeholders within education and sustainable development communities (UNESCO 2019b).

2.2 Engaging all stakeholders and actors in chemistry education

2.2.1 Promoting learning throughout society

Chemistry is a subject which, given its major implications, does not only concern chemists. Learning in matters of chemistry is therefore relevant for a broad group of actors, including citizens. The tripartite categorization of learning systems (Coombs and Ahmed 1973) helps to unpack the various dimensions of education and learning, including for green and sustainable chemistry education. It comprises formal, non-formal and informal education. Educational systems promote formal education and learning which usually follows a syllabus. Non-formal learning is also structured but usually takes place outside a formal learning environment, e.g. short term professional development courses. Informal learning arises from the learner's intended or unintended involvement in activities that are not undertaken with a concrete learning purpose in mind and takes place outside of organized educational frameworks. The ways in which green and sustainable chemistry learning can be integrated into these three dimensions of education are elaborated in chapters 4 and 5.

2.2.2 Who are the target audiences for green and sustainable chemistry learning?

University Students

A primary target group for in-depth green and sustainable chemistry learning are undergraduate and graduate students in chemistry, chemical engineering and related science disciplines. However, it is also essential to educate university students in social or business sciences who may go on to serve in potential leadership positions that influence how chemicals, and products containing chemicals are designed, produced and used.

Primary and Secondary School Students

Educating students in primary schools and secondary schools is equally important. It will generate interest and excitement among younger learners to explore chemistry as a tool to advance sustainable development, while also learning about potential adverse impacts of chemicals. For primary school learners, green and sustainable chemistry would normally be a part of broader science education, rather than being a self-standing topic of learning.

Change agents in the public and private sector

Beyond students in formal education, which is addressed in chapter 4, targeting stakeholders in management positions in the private and public sectors, and conveying to them the importance and potential benefits of green and sustainable chemistry is critical. Potential learners in this group include, rectors or deans of universities, managers of investment funds, government policymakers and others with potential influence in shaping science and innovation policies and practices.

Citizens

Last but not least, the public at large is an important target audience for green and sustainable chemistry learning, given the critical role that citizens have to demand change and their purchasing power as consumers. To reap the potential of consumers to advance green and sustainable chemistry, the topic needs to be included, for example, into broader product sustainability and awareness-raising campaigns. Product labels that portray hazard information and sustainability impacts are key to engage public audiences. Opportunities to reach this group are discussed in chapter 5.

2.2.3 Promoting a diverse student base

Lasker and Brush (2019) discuss the importance of engaging students from diverse backgrounds in science and chemistry education, including from disadvantaged communities and groups. Pedagogy that prioritizes the retention of comparatively underrepresented groups will help create a more diverse science, technology, engineering and mathematics (STEM) workforce. This in turn helps to ensure that societal challenges are better reflected in the work environment.

For example, women are historically underrepresented in STEM fields. Empowering women and girls in chemistry education will ensure their unique perspective is reflected, allowing for a more comprehensive understanding of sustainability challenges, and the promotion of chemical innovations which better consider UNEP's Objectives and gender.

Lasker and Brush (2019) propose three guiding principles to address these gaps:

1. Increasing inclusivity, diversity, and social justice in science, chemistry and engineering education, and developing student identities requires changes at the organizational and interpersonal level;

Box 2-3 Indigenous knowledge for green and sustainable chemistry teaching (Zidny and Eilks 2020)

Integrating diverse cultural components into chemistry teaching can help to enrich learning experiences while promoting the inclusion of different perspectives in the classroom. For example, by using local indigenous knowledge in chemistry lessons, students will gain a better understanding of environmental ethics and be encouraged to critically reflect on scientific methods and the need to adapt to local circumstances.

In Indonesia, a chemistry unit on pesticides presented the plant-based bio-pesticide used by the local Baydu community (called samara pungpuhunan) as a sustainable alternative to traditional synthetic pesticide chemicals. After learning about the traditional pest control practices of the Baydu, the students used chemistry concepts to elaborate on the differences between the pest control options. The students responded favorably to the intervention finding it personally relevant and interesting (Zidny and Eilks 2020).

2. Organized change leads to inclusion when it reflects and affirms the lived experiences of diverse members of the community (e.g. students, staff, faculty, administrators) and recognizes people with complex, multifaceted identities; and
3. Explicit pedagogical and social supports for students and faculty will help to transition their identities, knowledge and skills from the school world to the world of practice.

2.3 Learning topics and resources for effective green and sustainable chemistry learning

The Green and Sustainable Chemistry: Framework Manual (UNEP 2020) introduces topics which are relevant for green and sustainable chemistry learning. They include both scientific and technology topics, as well as complementary sustainability topics and concepts considered relevant for advancing the green and sustainable chemistry objectives and guiding considerations. This section of the Specialized Manual presents selected learning topics relevant for green and sustainable chemistry learning. A list of key organizations which offer access to courses and materials for green and sustainable chemistry education can be found in the Annex. General learning resources related to green and sustainable chemistry such as textbooks, academic publications and special journal articles may also be accessed in the Annex.

2.3.1 Essential complementary green and sustainable chemistry learning topics

In chapter 4 of UNEP's Green and Sustainable Chemistry: Framework Manual (UNEP 2020), chemistry and technology topics relevant for green and sustainable chemistry are introduced. They are:

- Biobased and renewable chemical feedstocks (e.g. carbon dioxide as a resource);

Box 2-4 Special Issue on Reimagining Chemistry Education: Systems Thinking, and Green and Sustainable Chemistry, Journal of Chemical Education, 2019 (Flynn *et al*. 2019)

In 2017, IUPAC launched a global project on Systems Thinking in Chemistry Education (STICE). The initiative was motivated by the desire to help equip chemists and citizens to address complex, global challenges. One outcome of the project is a 2019 Special Issue in the Journal of Chemical Education on "Reimagining Chemistry Education: Systems Thinking, and Green and Sustainable Chemistry". The Special Issue takes stock of the rapidly evolving literature on the incorporation of systems thinking into chemistry education, including its intersection with green and sustainable chemistry. A dedicated article in the Special Issue provides an outlook for (1) developing systems thinking resources for chemistry educators and students, (2) identifying chemistry education research needed to investigate and improve systems thinking approaches, and (3) investigating opportunities to apply chemistry-related systems thinking approaches in broader educational contexts (Flynn *et al*. 2019).

- Chemical innovation opportunities (e.g. solvents, water, grease and dirt repellents, flame retardants, surfactants, chemical preservatives);
- Process innovation opportunities (e.g. catalysis, batch vs. continuous processing, biorefineries);
- Opportunities for digitization (e.g. computer aided chemical screening)
- Potential of green and sustainable chemistry innovations in the energy sector (e.g. energy storage materials, solar fuels)

While these technological areas are important to include in education, moving towards a systems-thinking approach in green and sustainable chemistry education will require the inclusion of additional topics which are generally ignored in chemistry learning. Chapters 5-7 of the Framework Manual covers some of these from enabling policies, instruments and sectors to metrics and reporting. All these topics are relevant, however, based on expert consultation and an assessment of current chemistry curricula, the following topics have been identified as especially important to equip current and future chemists to advance UNEP's Ten Objectives and Guiding Considerations.

A list of the topics is provided here, for a detailed list of resources corresponding to each of the topics, please refer to the Annex.

Toxicology and eco-toxicology

Consistently identified by green and sustainable chemistry advocates as a critically undertaught topic. It's inclusion in the chemistry classroom will help students gain a better understanding of the harmful effects chemicals have on human health and the environment

Chemical hazard assessment and classification of chemicals

Awareness and knowledge related to how chemicals are classified around the world and frameworks for analyzing them will empower students to go on and improve the safety of their future workplace and make smarter decisions regarding chemical use or product design.

Life cycle assessment and thinking

Exposure to life cycle thinking and assessment methods is critical to develop professionals who will push for applying the concept at their future positions and will be capable of taking a leading role in effectively and responsibly carrying out these analyses.

Material and product design for sustainability and circularity

Covering important frameworks and concepts for sustainable and circular design will result in professional chemists that put sustainability considerations at the forefront of product design initiatives or researchers that develop materials to advance the circular economy.

Systems-thinking, SDGs and sustainability

Chemistry students with a deep understanding of the relationship between global systems and chemistry and an awareness of international sustainability frameworks and indicators will be better prepared to develop innovations without harmful tradeoffs that address major sustainability challenges.

Policy and regulatory frameworks

Communicating key regulations and policies related to chemicals and chemistry is essential. Students endowed with knowledge and skills related to these frameworks can contribute to strengthened science-policy spaces which are critical to advancing green and sustainable chemistry.

ACTION STEPS FOR EFFECTIVE GREEN AND SUSTAINABLE CHEMISTRY EDUCATION AND LEARNING

3

This chapter offers suggestions for educators and professionals who play a role in designing green and sustainable chemistry learning interventions within their organizations. It presents four action steps supporting the design, implementation and assessment of effective green and sustainable chemistry learning interventions and educational programmes. These action steps are meant to be relevant for professionals engaged in all spheres of learning; formal, non-formal and informal. They are listed below.

1. Identify and describe specific audiences for green and sustainable chemistry learning
2. Determine green and sustainable chemistry competencies for identified audiences
3. Design learning interventions and determine the corresponding learning objectives
4. Assess progress towards learning objectives and evaluate impact.

Key Chapter Takeaways:

- ✓ Green and sustainable chemistry learning interventions should be designed in a structured manner, beginning with the systematic identification and description of the target audience/s.
- ✓ Competency frameworks define the desired attitudes, skills and knowledge for a given target group and their development is encouraged to aid in the design of results-oriented learning interventions.
- ✓ The chapter presents three competency levels to help define the diverse learning needs of different target audiences for green and sustainable chemistry learning.
- ✓ Long-term and short-term learning assessments are essential to measure progress and effectiveness of learning interventions.

The value of instructional design for effective learning

Instructional design seeks to overcome deficiencies in the development of learning interventions. Such deficiencies, include, for example, targeting the wrong audience, ignoring learning needs of beneficiaries, or overloading learners with content. Since green and sustainable chemistry is a novel dimension of science and sustainability education, applying instructional design principles and methods is important to achieve desired learning results and impact.

Instructional design methods support educators to craft learning materials, methods and experiences such that learners acquire and are able to apply new knowledge and skills. The discipline follows a systematic process, ranging from assessing needs to evaluating the effectiveness of learning. A number of instructional design models exist, but many are based on the ADDIE model (Molenda 2003) with the five phases of design being: analysis, design, development, implementation, and evaluation.

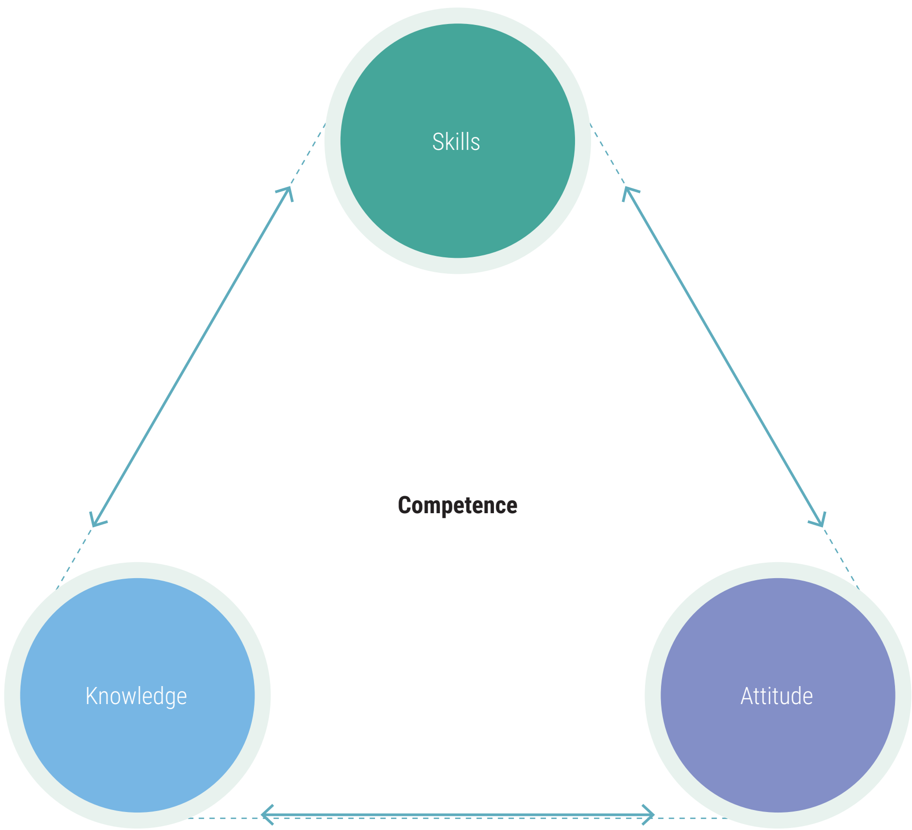
Development of a competency framework

To design and monitor results-oriented learning interventions, organizations have introduced competency frameworks. Dubois (1993) defines competencies as the "capability of applying or using knowledge, skills, abilities, behaviors, and personal characteristics to successfully perform critical work tasks, specific functions, or operate in a given role or position".

These frameworks can and have provided many organizations with valuable guidance to design effective learning programmes. Very few green and sustainable chemistry specific competency frameworks currently exist, but organizations which are interested in developing one may want to learn from these relevant examples.

- The WHO competency framework for health workers' education and training on antimicrobial resistance (WHO 2018) which was developed in the context of the WHO

Figure 3-1 **Attitudes, Skills and Knowledge for competency frameworks**



Global Action Plan on Antimicrobial Resistance adopted by Member States in May 2015.

- The IBM "Information Technology Job Skills and Competencies Framework" which is an example of a technical competency framework developed in the private sector (IBM 2016).
- In the area of teacher training, Grosch (2017) presents a competency standard for the technical and vocational education and training (TVET) system in ASEAN countries.

Distinguishing attitude, knowledge, and skills competencies

An important aspect in developing a competency framework is to distinguish between changes needed in attitude, skills and knowledge also referred to as the A.S.K model.

- **Attitude** refers to feelings, emotions, beliefs, values.
- **Skills** refers to the ability to do something (i.e. workplace skill) and are relatively easy to define and measure (e.g. performance in terms of time and precision).
- **Knowledge** refers to the ability to cite facts or concepts and is generally easy to measure.

Distinguishing between attitude, skills and knowledge is important, as this determines the design of specific learning interventions. Figure 3-1 provides a brief illustration how the three aspects featured in A.S.K can be applied to education and learning on chemical hazard assessment under the Globally Harmonized System for Chemical Classification (GHS) - an important resource for green and sustainable chemistry learning.

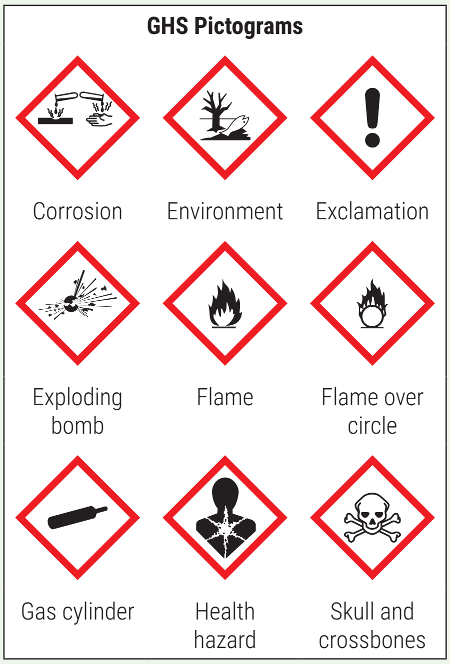
Box 3-1 Distinguishing between knowledge, skills and attitude competencies: Using the GHS as an illustration (adapted from UNITAR n.d.)

The GHS is an important global instrument relevant for minimizing or eliminating chemical hazards. It provides harmonized criteria for classifying and labeling chemicals and products. A wide range of actors have roles to play in GHS implementation, necessitating a variety of distinct learning interventions and approaches.

Knowledge
Learning that focuses on building and transferring knowledge may emphasize enabling the learner to identify and describe the three major GHS hazard groups and the nine pictograms. Researchers in a chemistry laboratory, workers in a chemical plant and consumers would be important target groups for this knowledge.

Skills
Learning which develops skills related to GHS may focus on the learner's ability to classify chemicals according to the scientific criteria provided in the GHS. A target group which should possess this skill are managers of companies which have chemical inventories or officials engaged in regulation.

Attitude
Learning which promotes certain attitudes would seek to convey the importance of GHS implementation to workplace safety and efficiency. An upper-level manager in a company which handles or produces chemicals or a head laboratory technician would be key targets to instill with this type of attitude.



3.1 Proposed action steps to design effective learning interventions

With an understanding of instructional design and competency frameworks, the process to design effective green and sustainable chemistry learning interventions can begin. The action steps are presented and described below.

Step 1 Identify learning opportunities and needs for specific target groups

Identifying specific targets groups within an organizational context is a critical first step towards scaling-up effective green and sustainable chemistry education. Educators in tertiary learning institutions, may, for example, systematically consider which degree programmes are suitable to feature green and sustainable chemistry education and which curricula may need to be adapted. The professional development department in a company may identify specific employees for which green and sustainable chemistry learning would have a particular impact. It is important here that you describe the employees' activities and the potential connection with green and sustainable chemistry.

Some potential learning audiences for green and sustainable chemistry learning may not immediately come to mind. Therefore, it is important to identify them in a systematic and creative manner. In vocational schools, for example, chemistry (including green and sustainable chemistry) is usually not taught as a priority topic but may indeed be relevant. Electricians and plumbing professionals, for example, have a choice of materials they use. Creating awareness and conveying knowledge of chemicals and products with less hazard potential empowers these groups to make informed choices and help create market demand for more sustainable products. . Using a gender-lens when targeting consumers can have a particularly strong impact, as more women are becoming leaders in raising awareness on chemical exposure in their communities (BRS 2019). Some other target groups that are important but not immediately obvious are consumers, waste management actors and government officials that are not directly involved in sustainability or science policymaking.

Step 2 Determine the desired competency level for identified target groups

In this section, three levels of competencies are offered to organize the diverse requirements that different target groups have for green and sustainable chemistry learning. Each level is accompanied by possible competencies. Keep in mind that these are meant to be a starting point for organizations and educators to develop their own competencies for their specific context. Adjustments may be needed and are encouraged such that competency frameworks are developed with maximal impact in a range of settings.

Recognizing different learning needs of different groups, a distinction is made between:

- Awareness and basic understanding of green and sustainable chemistry (Competency level 1)
- Solid knowledge and introductory skills for green and sustainable chemistry (Competency Level 2)

- Advanced green and sustainable chemistry knowledge and skills (Competency Level 3)

Collectively, the three competency levels should inform the development of effective and targeted learning interventions and programmes in formal, non-formal and informal education (see chapters 4 and 5).

Basic green and sustainable chemistry competencies

Competency Level 1

Learners are able to discuss specific technological and enabling aspects of green and sustainable chemistry and chemical hazards. They can utilize a range of reference and resource material and possess an understanding of green and sustainable chemistry innovations.

Target audiences for level 1 green and sustainable chemistry competencies

- Consumers
- Government officials outside environment/health domains
- Decision-makers and workers in private sector enterprises with some relevance to chemicals and green and sustainable chemistry

Many actors and change agents are not directly engaged in green and sustainable chemistry innovation. However, their awareness and action may impact the way chemistry is practiced, and the types of chemicals placed on the market. Such awareness may be achieved through diverse learning interventions which are appropriate for different groups. Consumers, for example, have a choice of products to purchase. Developing a basic understanding of green and sustainable chemistry and how it figures into product manufacturing and design may affect purchasing habits. Citizens with a basic level of competency may also engage with their community or participate politically in a manner which contributes to the promotion of green and sustainable chemistry.

Developing the level 1 competency ideally begins in primary school, where introducing green and sustainable chemistry concepts can set students on the path towards responsible consumption or inspire them to eventually pursue further education in green and sustainable chemistry. Government officials without a specific focus on sustainable policymaking may be guided by this basic awareness to promote science-research funding, curricula development or sustainable procurement frameworks with specific green and sustainable chemistry considerations. Finally, targeting private sector decision-makers to achieve this competency level may influence the choices they make at the supply-chain or business operation levels such that they advance the concept.

Taking learning opportunities for these target groups into account, the following level 1 competencies are proposed:

- Basic knowledge that chemicals are hazardous to human health and the environment and that products contain these chemicals.

- Understanding that green and sustainable chemistry innovation can lead to chemicals and products that are non-hazardous while delivering desired functions.

- Awareness that chemistry offers solutions to address a range of sustainability challenges (e.g. climate change)

Solid green and sustainable chemistry competencies

Competency Level 2

Learners are able to discuss specific technological and enabling aspects of green and sustainable chemistry and chemical hazards. They can utilize a range of reference and resource material and possess an understanding of green and sustainable chemistry innovations.

Target audiences for level 2 green and sustainable chemistry competencies

- Deans or heads of relevant university departments
- Students in fields with some relevance to green and sustainable chemistry (i.e. finance, business, medicine, engineering, government)
- Business leaders engaged in sustainability topics and chemistry and materials science.
- Government officials involved in sustainable policy-making
- Plant operators
- Product designers

For competency level 2, a range of actors are targeted whose actions directly influence the way chemistry is practiced. Possessing this level of competency, leaders in companies engaged in chemistry activities or employees with responsibilities specific to sustainability may choose to pursue the implementation of a specific innovation or establish a company vision which includes green and sustainable chemistry considerations. Plant operators, equipped with the ability to utilize relevant reference material, may research ways in which green and sustainable chemistry practices can lead to a safer work environment. Government officials with roles of particular interest to sustainability may enact favorable policies (e.g. fostering girl' participation in STEM disciplines) which drive green and sustainable chemistry innovation, as they are knowledgeable about their potential to address sustainability challenges. Product designers with this competency may explore novel sustainable product innovations. Secondary school students endowed with solid green and sustainable chemistry knowledge will be able to go-on to university, or the workplace, and contribute to the multidisciplinary environment needed to advance UNEP's 10 Objectives and Guiding Considerations.

Taking learning opportunities for these target groups into account, the following level 2 competencies are proposed:

- Sound knowledge on chemicals of concern regarding their presence in the environment and the corresponding classification frameworks (UN GHS).

- Robust understanding of the UNEP's 10 Objectives and Guiding Considerations for green and sustainable chemistry including the ability to identify actions which can advance a given Objective.

- An understanding of the roles which different stakeholders can have in the transformation to green and sustainable chemistry.

- Ability to provide examples on how green and sustainable chemistry innovation help to address sustainability in sectors such as health, agriculture, electronics etc.

Advanced green and sustainable chemistry competencies

Competency Level 3

Learners can discuss, teach and generate new knowledge on green and sustainable chemistry. They are equipped to lead initiatives focused on the development and implementation of green and sustainable chemistry innovations.

Target audiences for level 3 green and sustainable chemistry competencies

- Chemistry students in undergraduate and graduate tertiary education
- Scientists and researchers in the private sector
- Scientists and researchers in public research institutions
- Government officials and policymakers in highly relevant positions (i.e. ministry of environment, department of pollution control, regulatory agencies)

University students of chemistry along with researchers engaged in chemistry, material science and engineering innovation require the most advanced levels of green and sustainable chemistry competencies. Possessing this suite of knowledge, skills and abilities will allow these actors to drive the concept of green and sustainable chemistry forward through the development of new innovations and the identification of opportunities. Those with this level of competency should be well-versed in consulting with experts in other disciplines to implement and develop chemistry innovations. The entirety of their work should consider green and sustainable chemistry and they should be able to disseminate their knowledge to a wider, less informed audience.

The four advanced competencies presented here draw upon the valuable work undertaken by the American Chemical Society (ACS). During the ACS Green Chemistry Education Road Map process, stakeholders in green chemistry and engineering along with those in chemistry education research developed a green chemistry competency framework for university students. It features three core competencies (MacKellar *et al.* 2020): (1) Chemical design; (2) Process design and (3) Product design, all with the goal to improve sustainability performance. Given the wider scope of this Manual to also address sustainable chemistry, a fourth area which covers capabilities to understand the interface of chemistry and broader sustainability challenges has been added.

This results in the following four advanced green and sustainable chemistry competencies:

1. Advanced capability to shape chemistry innovation to address sustainability challenges.

2. Advanced capability to design chemicals with improved sustainability performance

3. Advanced capability to design chemical syntheses and processes with improved sustainability performance.

4. Advanced capability to design products with improved sustainability performance

1. Advanced capability to shape chemistry innovation to address sustainability challenges

Learners will understand the relationship between chemistry and sustainability and are able to develop and recognize chemistry-related opportunities and solutions which harness interdisciplinary collaboration to advance sustainability from a system-wide point of view.

The first advanced competency area focuses on broader "Sustainability Challenges and Opportunities" using a systems thinking approach. It captures the inter-connectedness of ecological, social and economic systems and how they are affected by chemistry activities. It also involves an understanding of the contribution chemistry can make to address sustainability challenges, without creating negative impacts. For academic sustainability learning, this entails enabling students to plan, conduct, and engage in sustainability research and to build capacity to develop chemistry-based solutions for sustainability challenges. Under this competency, students are able to perform analyses across temporal and spatial scales and consider the implications of actions on other stakeholders (Wiek, Withycombe and Redman 2011). In summary, those with a proficiency in this competency should be able to consider the impact that any chemistry action may have, with the objective of "promoting an economically, socially and environmentally sustainable future for our planet and for present and future generations" as stated in the Rio Declaration, 1992.

2. Advanced capability to design chemicals with improved sustainability performance

Learners will understand chemical hazards and are able to design, select, or choose chemicals (or products containing chemicals) with improved sustainability performance across the life cycle.

This advanced competency focuses on advancing "Sustainable Chemicals". It covers abilities needed to advance the discovery, evaluation, and selection of new and existing chemicals with improved sustainability performance throughout the life cycle, while performing desired functions. This competency area involves using tools and methods that distinguish benefits and drawbacks of specific chemicals.

3. Advanced capability to design chemical processes and syntheses with improved sustainability performance

Learners will understand how chemicals and materials are prepared through the transformation of raw materials via synthetic pathways and chemical processing units. They will be able to design, select or recognize more sustainable chemical processes with greater resource efficiency and minimized releases of pollutants and other adverse impacts.

This third advanced competency area focuses on "Sustainable Processes". It covers the discovery, selection and promotion of synthetic pathways and chemical processes which improve the sustainability and safety of production for both existing and new chemicals and materials. It also encompasses the ability to use tools and methods to identify, evaluate, select, and optimize pathways and processes. For chemists and chemical engineers, this means the selection or design of a sustainable, optimized process to make a desired molecule or material through the systematic identification and life cycle evaluation of potential pathways. Under this competency, chemists and chemical engineers should also have the ability to acknowledge and evaluate trade-offs associated with alternative processes.

4. Advanced capability to design products with improved sustainability performance

Learners will understand how chemicals can be used and integrated into products to achieve the best benefit to customers while minimizing life cycle sustainability impacts. They will be able to use this knowledge to design, select or promote products which are safer, and more sustainable from a life cycle perspective.

The fourth advanced competency focuses on "Sustainable Products" and their chemistry dimension. It recognizes that chemicals chosen to perform a specific function (or confer desired performance attributes) in a product should be selected with product life cycle impacts in mind. This competency widens the system perspective beyond chemistry, by fostering a broader understanding of sustainability considerations across the life cycle of products. This competency area is essential to ensure alternative products are designed using chemicals and materials with minimized environmental and human health impacts. For chemists, this competency means learning more about the importance of product design, an interdisciplinary topic generally not addressed within the domain of chemistry.

Step 3 Determine learning objectives and design learning interventions

The importance of developing learning objectives

Developing learning objectives is of crucial value to effective green and sustainable chemistry learning interventions. Learning objectives are statements of what learners should know or be able to do following participation in a particular learning activity. They closely relate to, but are more specific than, competencies. Learning objectives help to clarify, organize and prioritize the design and methods of learning interventions to advance green and sustainable chemistry. Educators may take the core competency areas presented above as a starting point to design learning objectives and outcomes for individual activities or for series of learning interventions.

Ideally, learning objectives and performance expectations should be agreed upon across different learning initiatives that have similar target audiences (MacKellar *et al.* 2020). The four core competency areas could provide a starting point for discussions to choose learning outcomes which are consistent among relevant institutions.

Box 3-2 Example of detailed learning objectives for university chemistry students for Competency Area 1 on Sustainable Chemicals (MacKellar *et al*. 2020)

To guide specific learning interventions, core competencies can be expanded upon using accompanying detailed sub-competencies and learning objectives that are relevant for specific target groups and contexts. The detailed competencies and learning outcomes below, relevant to competency area 1, were developed by the ACS for students at the university level.

- Ability to collect, analyze, evaluate the quality of, interpret and compare data that can be used to select/design new chemicals/ materials or chemical/ material alternatives with enhanced function and reduced environmental, health, and safety impacts.
- Ability to use life cycle thinking to reduce the environmental footprint of chemicals and design chemicals and materials for sustainability.
- Valuing collaboration and seeking expert multidisciplinary consultation with toxicologists, eco-toxicologists, engineers, ecologists, biogeographers, and environmental chemists, etc.
- Ability to use decision-making knowledge and tools to understand, evaluate, and compare tradeoffs to optimize the impact–benefit ratio of chemicals from a life cycle and systems perspective.

Learning interventions to achieve outcomes

To reach the designated outcomes, proper learning interventions must be designed and implemented. The competency levels introduced in step 2 can inform the design of interventions such that they are suitable for the selected target audience. Table 3-1 provides examples of learning interventions for specific target audiences and learning objectives.

Table 3-1 **Using competency levels and learning outcomes to design learning interventions**

Selected Target Audiences	Competency Level	Learning Outcome	Sample Learning Products and Interventions
‣ Consumers ‣ Government officials ‣ Decision-makers in the private sector ‣ Primary and Secondary School Students	1	Learners have a general understanding of chemicals hazards as well as basic green and sustainable chemistry concepts. They can communicate its importance and deliberately make choices and take actions which contribute to advancing it.	‣ Development and dissemination of introductory awareness raising materials which introduce the green and sustainable chemistry concept. ‣ Short videos or on-line tutorials ‣ Integration of green and sustainable chemistry into broader sustainability education
‣ Deans or heads of relevant university departments ‣ Business leaders ‣ Government officials involved in sustainable policy-making ‣ Plant Operators ‣ Product Designers ‣ Environmental Compliance Officers	2	Learners are able to discuss specific technological and enabling aspects of green and sustainable chemistry and chemical hazards. They can utilize a range of reference and resource material and possess an understanding of green and sustainable chemistry innovations.	‣ Interactive green and sustainable e-learning course aimed at policy-makers or private sector actors. ‣ Short green and sustainable chemistry “talks” by already competent professionals in the organization. ‣ E-learning course on important regulatory frameworks and MEAs related to chemicals with links to green and sustainable chemistry practices and innovations.
‣ Chemistry students at the graduate level ‣ Chemistry experts in the private sector	3	Learners can discuss, teach and generate new knowledge on green and sustainable chemistry. They are equipped to lead initiatives focused on the development and implementation of green and sustainable chemistry innovations	‣ Self-standing full-semester green and sustainable chemistry courses. ‣ Research design courses focusing on green and sustainable chemistry research opportunities. ‣ Learning and coaching programmes on topics relevant for green and sustainable chemistry entrepreneurship, such as patent development, financing and marketing.

Step 4 Assess learning outcomes and impact

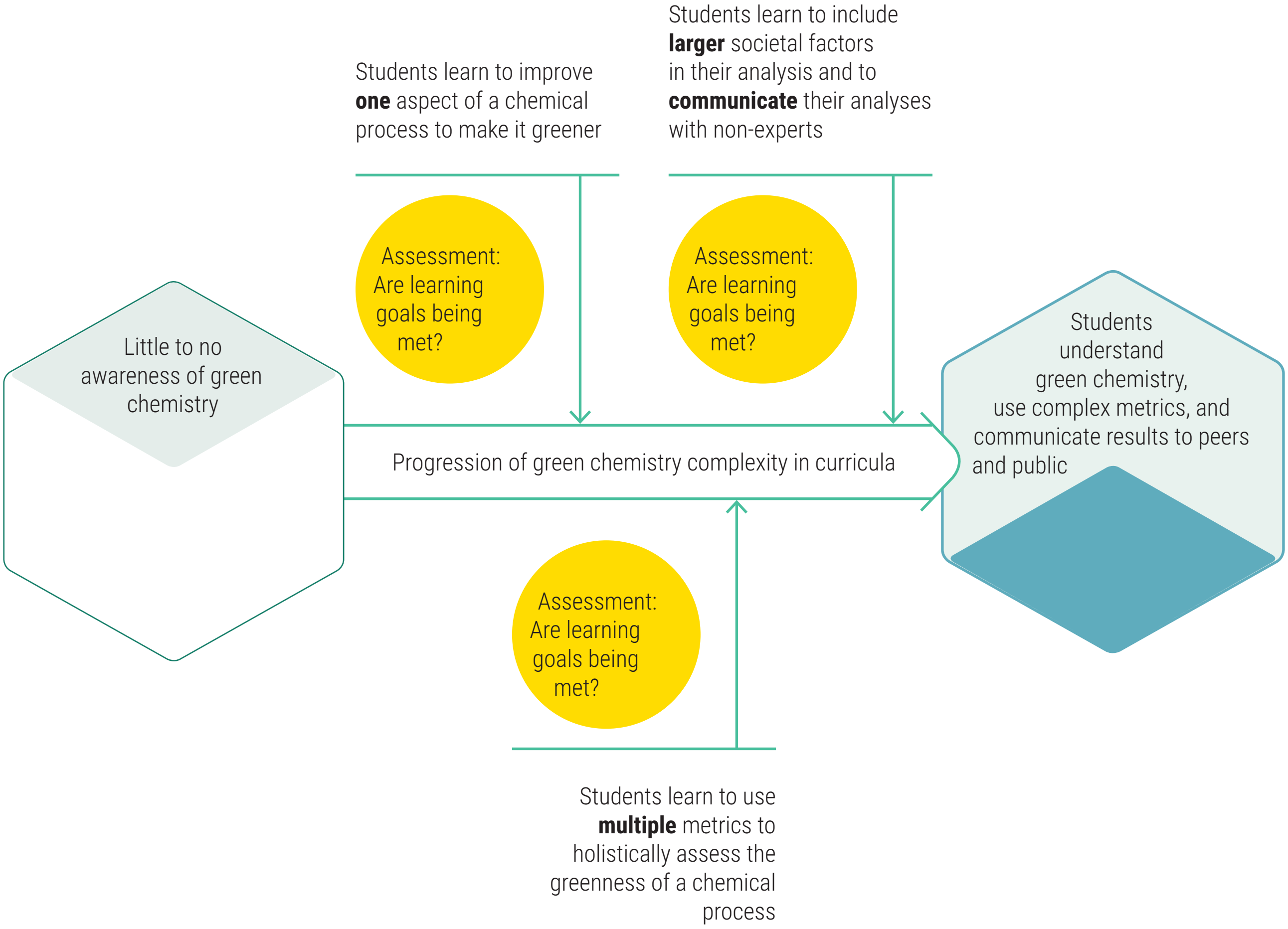
Assessing learning outcomes and impacts is an essential component of effective green and sustainable chemistry education and learning. It is important both immediately following a learning activity, as well as after a cycle, to reveal at different stages how well learners have retained and are able to apply, knowledge, skills or attitudes. Assessing the ultimate and long-term impact of learning is more complex. This would require designing an assessment which tests whether or not the behavior changes, skills and knowledge obtained during learning (e.g. by chemists) have resulted in advancing UNEP's 10 green and sustainable chemistry objectives and guiding considerations.

Assessing green and sustainable chemistry learning outcomes

Instilling learners with green and sustainable chemistry competencies is a step-by-step process, featuring various learning interventions and assessments. Figure 3-2 features a framework which depicts the gradual progression of green and sustainable chemistry competency developments. Learning assessments are conducted at strategic points in the process (Armstrong *et al.* 2018). These assessments of learning outcomes help to iteratively improve existing courses, provide validity to new curricula, and increase buy-in from faculty and students.

A comprehensive review of green and sustainable chemistry assessment approaches is presented by Armstrong *et al* (2018). Approaches used include a combination of qualitative and quantitative tools. The tools are chosen for their ability to efficiently measure desired learning outcomes. They assess student and instructor knowledge, attitudes, motivation and values, laboratory skills, and communication of chemistry concepts.

Figure 3-2 **Progress of complexity in green chemistry curricula that helps students understand, apply and communicate green chemistry** (adapted from Armstrong *et al*. 2018, Page 2)

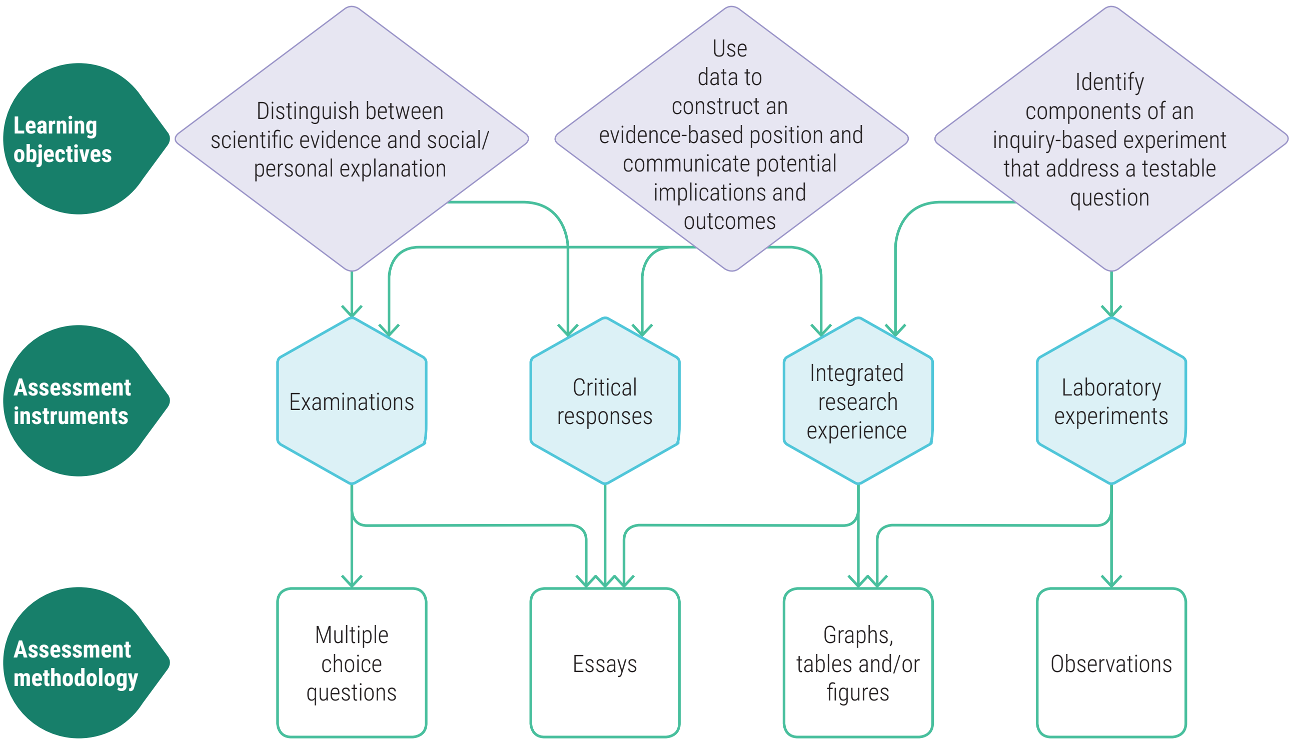


Assessing scientific competencies through green and sustainable chemistry education

An alternative approach to assessments is to use green and sustainable chemistry learning as a vehicle to advance and evaluate broader scientific competencies. This is a creative approach to insert green and sustainable chemistry into the science education landscape resulting in enhanced credibility for the field. This approach was carried out at Bentley University when core learning objectives for students in natural and applied sciences were used to assess the learning outcomes of an undergraduate course on "Chemistry of Sustainable Products" (Bouldin and Folchman-Wagner 2019).

The course was designed for business students interested in the development of environmentally benign consumer products. The learning assessment was conducted using the Test of Scientific Literacy Skills (TOSLS) using various assessment methodologies. It was given at the beginning of the course, prior to the presentation of any course materials, and again during the last class meeting of the semester (Bouldin and Folchman-Wagner 2019). Figure 3-3 provides a sample scheme on how assessment instruments and methodologies may be used to assess broader science learning objectives through a green and sustainable chemistry course.

Figure 3-3 **Course Learning objectives and assessments of a green chemistry course for business students at Bentley University in the United States** (adapted from Bouldin and Folchman-Wagner 2019, page 4)



GREEN AND SUSTAINABLE CHEMISTRY IN **FORMAL EDUCATION**

4

Chapter 4 offers examples, resources and key considerations for educators within primary, secondary and tertiary level learning institutions. For each stage of formal education, the chapter introduces conceptual issues, as well as illustrations and examples to draw from. The chapter also includes cross cutting topics, such as innovative laboratory experiments and learning methods, curriculum development and reform, and capacity development for educators.

Key Chapter Takeaways:

- Curriculum reform and teacher capacity-development are two critical routes to long-lasting and meaningful change in the chemistry education landscape.
- Each stage of the formal education system presents an opportunity for green and sustainable chemistry learning with unique benefits and considerations.
- The academic laboratory is an important setting for green and sustainable chemistry learning and the design of experiments should be done systematically with clear goals.
- Innovative learning methods related to games, social media and field trips can be leveraged to promote green and sustainable chemistry learning.

4.1 What is formal education?

While education systems vary across countries, formal education and learning may generally be divided into the following stages: early childhood education, primary education, secondary education, and tertiary or higher education. In many countries, the latter can be split into bachelor's (or equivalent level) and post-bachelor's (masters and doctoral levels) (UNESCO 2012). Figure 4-1 provides an example of the formal education system in Brazil (ACS 2016).

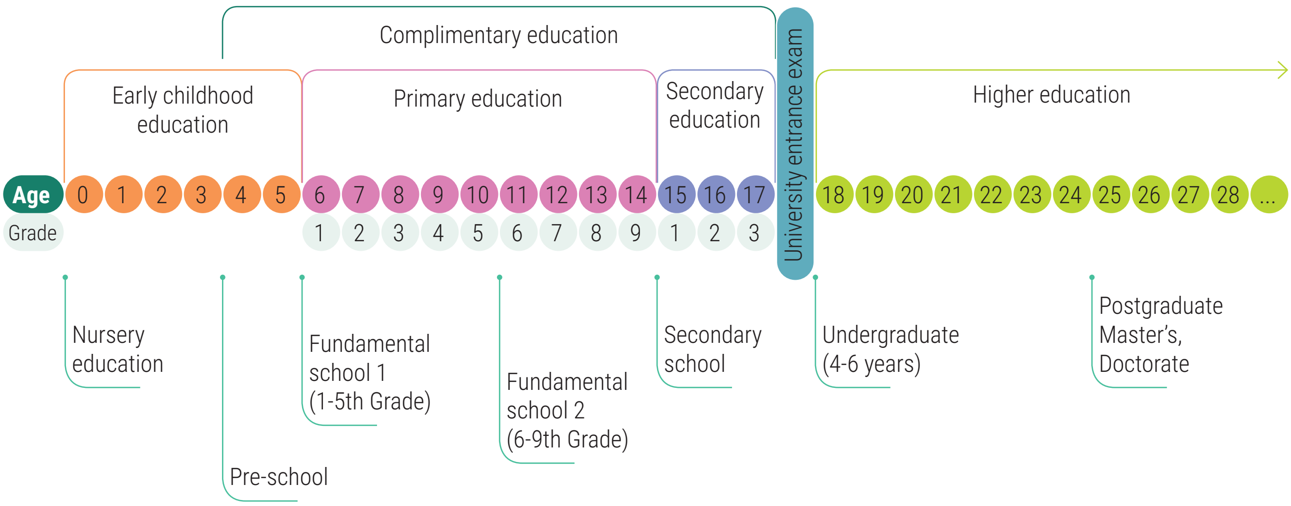
An educational process is formal when it is structured and has a curriculum (Dib 1988). Consistent across formal education systems is the establishment of learning objectives, often in the form of a syllabus, along with outcome measurement (e.g. through tests or other assessments). Formal education also involves regular communication between the teacher and the student.

Important questions to consider for how to best integrate green and sustainable chemistry perspective into formal education, include the following:

- How can green and sustainable chemistry concepts be integrated into existing chemistry education curricula, as well as related scientific disciplines?
- How can green and sustainable chemistry topics be integrated into broader ESD curricula and courses?
- What is the potential to develop and scale-up self-standing curricula and degree programs with a focus on green and sustainable chemistry?

This chapter seeks to touch on all these questions. It presents examples of strategies, courses, and materials which strive to put green and sustainable chemistry learning into practice in various contexts at each stage of the formal educational process.

Figure 4-1 **Chemistry in the Brazilian formal education system** (adapted from ACS 2016, page 9)



4.2 Institutionalizing green and sustainable chemistry in formal education

4.2.1 Curriculum development and reform

Curricula are at the heart of formal chemistry education. They can be understood as a formalized collection of lessons, assessments, and other academic content taught in a school, program, or class usually with support of a teacher. Curriculum reform involves a number of key considerations, including changing the concepts of learning and competencies, altering the role of teachers and students, and recognizing evolving contexts (Halinen eds. 2015). Achieving this is not necessarily an easy task. Impeding factors may include, for example, institutional lock-in from a long tradition of teaching chemistry in a certain way, or competition with other important disciplines for attention and time. However, once green and sustainable chemistry considerations are integrated into a curriculum, the concept is likely to gain recognition and support, and create long lasting impact.

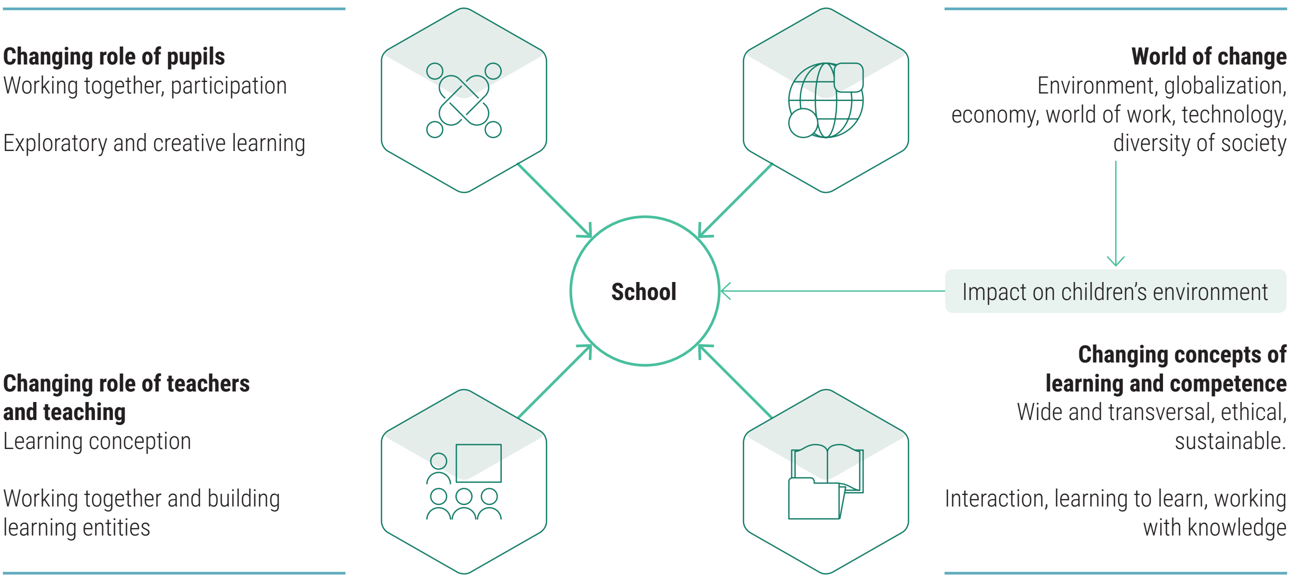
Valuable resources and case examples exist to aid in developing and reforming green and sustainable chemistry curricula. They can be found in the Annex.

4.2.2 Capacity-building for teachers

Given the crucial role teachers play in enacting societal change and advancing sustainability, developing the capacity of educators to deliver green and sustainable chemistry learning is essential. Targeting pre-service teachers that are participating in an educational degree program is an effective way to instill values and skills related to green and sustainable chemistry. Pre-service initiatives exist, but gaps remain, and greater efforts are required to equip future teachers to go on to foster systems-thinking and address sustainability topics in the classroom (Flynn *et al.* 2019).

- In Malaysia a green chemistry module with 10 experiments was successfully piloted with

Figure 4-2 **Four keys to curriculum reform** (adapted from Halinen eds. 2015)



future science educators(Karpudewan, Ismail and Mohamed 2009).

- A 6-week course in Germany integrated sustainability issues into pre-service chemistry teaching (Burmeister and Eilks 2013).

Educating teachers who have already completed their formal training is equally important. This can be achieved though professional development activities, such as train-the-trainer workshops, mentor networks, or continuing education courses (Karpudewan, Ismail and Mohamed 2009). Establishing networks of educators that participated in a certain course or workshop is a valuable option to extend the impact of these types of initiatives.

- In the US, a National Science Foundation (NSF) capacity building initiative featured Green Chemistry in Education Workshops for teachers of all formal education stages (K-12, community college, university) (NSF 2011).
- Beyond Benign leads teacher initiative programs which train primary and secondary school teachers to become green chemistry ambassadors. These ambassadors go on to lead train-the-trainer workshops and teach online courses for other teachers (Beyond Benign 2021) .
- In Brazil, following a workshop on green chemistry experiments in rural areas, a social media group was formed to encourage continued exchange of ideas and experiences (ACS 2016).
- Educator networking is an important aspect of the Global Greenchem Innovation and Network Programme executed by Yale University and the United Nations Industrial Development Organization (UNIDO) with financing from the Global Environment Fund (GEF) (GEF 2020).

The use of these illustrative examples to develop new capacity-development activities is encouraged with additional valuable learning materials and resources available in the Annex.

Box 4-1 Online course for secondary school teachers to promote green chemistry in the classroom (Zuin et al. 2021)

A socio-critical and problem-oriented approach was taken to develop a 10-hour online course for secondary school teachers on chemistry and sustainability. The course is offered free of charge by the Federal University of São Carlos (UFSCar) in Brazil. It focuses on innovation in chemistry teaching and learning to help secondary educators promote scientific literacy and green and sustainable chemistry awareness. A number of case studies are featured, for instance, on promoting a balanced view of the biorational control of insects in Brazil. The course was the final deliverable of an IUPAC Project designed to introduce green chemistry in higher education. It is available in Portuguese and English. Within the first two years of its launch in November of 2019, almost 3600 teachers had completed the course(Zuin *et al*. 2021) .

4.3 Green and sustainable chemistry learning at each stage of the formal education system

4.3.1 Primary Education

Early exposure of children to green and sustainable chemistry will nurture a future generation of citizens and scientists that understand sustainability challenges and are prepared to address them. Some learners may go on to pursue careers in science or chemistry with a sustainable mind-set. Others will be equipped to be scientifically literate citizens and consumers.

Learning by doing is particularly important at this early stage. Young students often appreciate experiential learning and respond well to visual representation and interaction. Table-top experiments, interactive lessons and games are therefore useful activities during early education. There are many examples and activities available which are relevant to green and sustainable chemistry learning.

- The ACS has developed four simple and inexpensive green chemistry interactive displays for children which are designed to promote hands-on interaction (Hakim n.d.). They include activities comparing the efficacy and environmental impact of dish soaps with and without phosphate additives and demonstrating the solubility of bio-degradable packaging materials.
- Beyond Benign has developed grade specific lesson plans and activities which encourage basic systems thinking while conveying green and sustainable chemistry concepts such as biomimicry, resource management and hazard emission mitigation (Beyond Benign n.d.).
- Young students may also appreciate and learn from observing their instructor integrating green and sustainable chemistry actions into classroom activities i.e. by using recycled soda bottles as experimental vessels, conducting microscale lab exercises and performing proper clean-up (Ause 2018).

4.3.2 Secondary education

The secondary level of education is an important crossroads along the chemistry learning pathway. It is at this stage that chemistry begins to be taught as a separate subject. It is also when many students begin to feel disinterested in the subject (See examples below). Nonetheless, due to the rapidly increasing environmental consciousness

Box 4-2 Chemistry and Water - A hands on activity for systems-thinking (Ause 2018)

As part of a 7th grade science course at Greenhills Highschool in Michigan, USA, the analysis of the water quality of a nearby stream was used as an entry point for green and sustainable chemistry learning. The student assessed how healthy the stream was for living organisms through the collection of basic data such as pH and temperature. Students then explored how nearby human activities may affect the water quality as determined through their measurements. The collected data was analyzed and formally presented to the local community. Systems thinking was encouraged by considering the stream's relationship with its environment, and by connecting the lesson to water resource issues in other parts of the world (Ause 2018). Though much of this activity may be considered environmental chemistry, its hands-on nature and community engagement element, can introduce young learners to important considerations related to green and sustainable chemistry in a contextualized and engaging manner.

Box 4-3 Green and sustainable chemistry in vocational education

Many secondary level students continue or diverge their educational path by attending vocational schools where they are prepared to enter the workforce technicians or trade professionals. Examples of vocational professions include electricians, truck drivers, hair stylists, or medical technicians. Educating vocational students about green and sustainable chemistry can help to form a class of trade professionals who put sustainable solutions into practice in their day-to-day work.

In Kenya, vocational training for electrical and mechanical trades includes environmental management lessons and considerations especially with regards to disposal of-waste and oil (Dubois *et al*. 2010). In Canada, green and sustainable chemistry concepts are emphasized in construction training through learning on the recycling of construction materials and sawdust. Automotive technician students may learn green and sustainable chemistry relevant techniques such as how to perform oil changes with recycled oil, safer disposal methods or the use of water-based paints (Taylor and Creech 2013).

among young people, a golden opportunity has emerged to re-capture the imagination of secondary school chemistry students by linking chemistry with sustainability issues. Various learning materials are available to support the implementation of green and sustainable chemistry at the secondary level, they can be accessed in the Annex.

- Malaysian chemistry students at the secondary level felt that chemistry experiments were not interesting and that their participation in learning was not encouraged (Karpudewan and Kulandaisamy 2018). The same study revealed that students experienced anxiety working with hazardous chemicals which hindered their interest and ability to learn.

- In Nigeria, 300 high-school level chemistry students were asked what anxieties they had in the chemistry classroom. 77 percent answered that "Chemistry is too abstract because we've never seen most of the things being taught" (Jegede 2007).

- In Sweden, where enrollment in chemistry programs at the university level is decreasing, survey found that a lack of context in secondary school chemistry studies resulted in students feeling disinterested in their chemistry courses(Broman, Ekborg and Johnels 2011).

Another approach to capture the attention of secondary chemistry students is by alerting them to the hazards of chemicals. Real-world cases of chemical pollution may be presented followed by discussions on the solutions offered by green and sustainable chemistry.

- Secondary school students in Michigan, USA were tasked with investigating the high-profile lead contamination of a nearby cities' drinking water, including its chemistry, engineering, environmental science and public relations aspects. The project involved research on how the problem began, its environmental and health effects and the current remediation plan (Ause 2018).

- In Italy, students attended a one-day conference where they were presented with images and information related to well-known cases of environmental pollution. They were then encouraged to reflect on the causes of the disasters and the solutions offered by green chemistry (Mammino 2015).

4.3.3 Bachelor (or equivalent level) tertiary education

To foster a new generation of "green and sustainable chemistry innovators", holistically integrating sustainability considerations and green and sustainable chemistry concepts into bachelor-level curricula is essential. Relevant disciplines which should be targeted include chemistry, chemical engineering, biochemistry, environmental science and other chemistry-oriented fields of study.

Box 4-4 Systems-thinking and green and sustainable chemistry using elemental cycles

Chemistry units related to global element cycles are a useful approach to introduce green and sustainable chemistry concepts while engaging students in systems thinking and interdisciplinary learning. In a project designed for students at a secondary school in Germany the phosphate cycle was used as a vehicle to teach chemistry students about plant biology, recycling processes, food supply considerations and political issues associated with the elements use as a fertilizer (Zowada *et al*. 2019). The unit was taught using a combination of phosphate recovery and plant growth experiments along with pre-and post-laboratory learning. The majority of the students reported having learned a lot about phosphates and that they would be interested in future news about phosphate fertilizers.

While sustainability concepts are gaining momentum at this level, they are at times tokenized, with green and sustainable chemistry courses often offered as electives and not required for graduation (Zuin 2019). Roadblocks hindering undergraduate curricula reform include crowded curricula, time-consuming material development, institutional inertia and resistance from faculty members (Klingshirn and Spessard 2009). However, given the momentum of green and sustainable chemistry education and an evolving student body that is more interested in sustainability, opportunities are emerging to overcome these challenges.

Strengthening interdisciplinary education

Interdisciplinary learning and collaboration at the undergraduate level is critical to convey to learners the diverse knowledge and skills that are required to develop and scale-up green and sustainable chemistry innovations. Chemistry students benefit from the inclusion of subjects such as toxicology, ecology, geography, biology, engineering and environmental science. It is also key to foster an understanding of chemistry's interface with business, government and finance. Student engagement with professional scientific networks and exchange with experts should be encouraged and facilitated. This type of networking can lead students to access new knowledge and prepare them to effectively operate in professional interdisciplinary environments (MacKellar *et al*. 2020).

Educational actors around the world are recognizing the advantages of interdisciplinarity to improve chemistry education and advance sustainability objectives.

- In India a new education policy is expanding chemistry education to include more multidisciplinary perspectives, with Shiv Nada University (SNU) as a leading example. Undergraduate chemistry students at SNU are required to take courses in physics, statistics, biology and computer programming (Padma 2020).

- In the United Kingdom, the Royal Society of Chemistry (RSC) has developed an online course to teach business and entrepreneurial skills relevant for chemistry innovation (RSC 2012).

Vice versa, it is key that students in biology, business, medicine, engineering and public policy gain exposure to green and sustainable chemistry concepts. This can contribute to forming a class of future professionals who will consider the benefits of green and sustainable chemistry and work to advance UNEP's Ten Objectives and Guiding Considerations.

- At the University of Creighton in the USA a course on "green chemistry and sustainability for non-science majors" communicates fundamental green chemistry concepts, while demonstrating the connection between chemistry and the fate of the earth. Specific themes covered include energy use, pollution, waste prevention, and safety. Best practices for communicating scientific principles and policies to different audiences are also emphasized (Gross 2013).

- At Bentley University in the USA, a course on "Chemistry of Sustainable Products", uses laboratory exercises and an integrated research experience to train future business leaders in sustainable product design (Bouldin and Folchman-Wagner 2019).

Integrating green and sustainable chemistry into university chemistry curricula

Curriculum modification is a pathway to long-lasting and meaningful integration of green and sustainable chemistry into university-level learning. Several approaches exist with differing levels of commitment and engagement. One is amending existing chemistry curricula with elective or mandatory green and sustainable chemistry courses.

- Sichuan University in China launched a compulsory online course on green chemistry for chemistry undergraduates (Zuin *et al.* 2021). The course is one example of the many activities being carried out in China to advance green and sustainable chemistry education and research (Figure 4-3) (Wang, Li and He 2018). A key learning objective of the course is to comprehend the basic principles of green chemistry such that they can be applied to address sustainability challenges.

- Several other universities around the world offer similar courses including the Federal University of Sao Carlos in Brazil , University of Cape Town in South Africa, The University of Dodoma in United Republic of Tanzania, and the National University of La Plata in Argentina (Zuin *et al.* 2021).

Integrating green and sustainable chemistry considerations directly into traditional chemistry curricula is a second, perhaps more challenging approach. Those who look to take this approach must consider the concern which some educators have that morphing chemistry curricula towards sustainability will result in the exclusion of foundational chemistry principles (Klingshirn and Spessard 2009). To address this and other challenges associated with chemistry curriculum modification, valuable resource materials have been developed.

- The ACS anchoring concepts content maps have been revised to include linkages between green chemistry and core chemistry topics (Holme *et al.* 2020).

- In Table 4-1 Aubrecht (2019) provides topical connections between key general chemistry and organic chemistry content with green chemistry principles

Figure 4-3 **Framework for the development of green chemistry in China** (adapted from Wang *et al.* 2018, page 2)

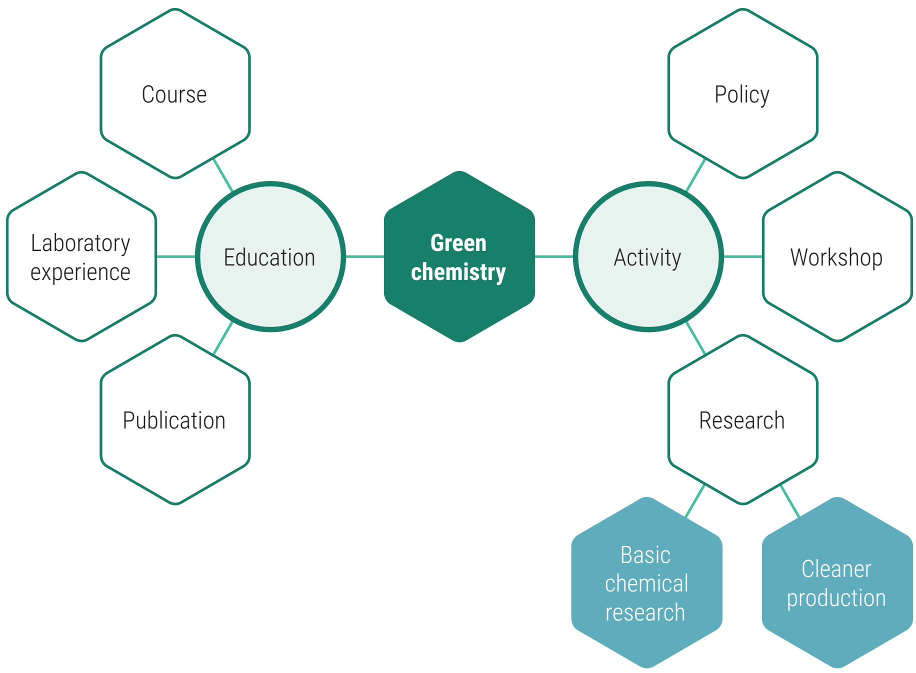
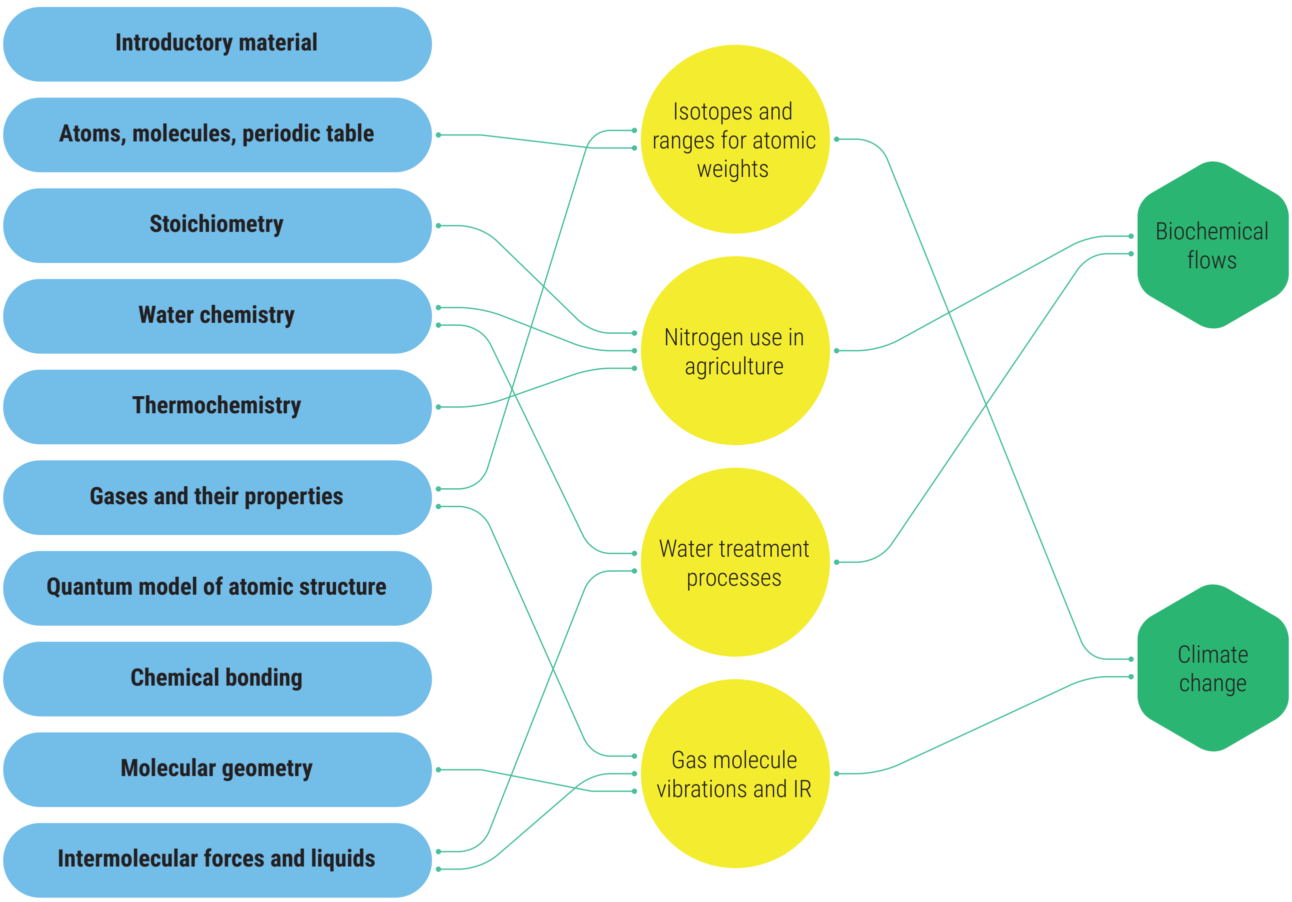


Table 4-1 **Topical connections between general chemistry and green chemistry concepts** (Aubrecht *et al.* 2019)

General chemistry concept – ACCM enduring understanding	Green chemistry connections
Atoms have unique chemical identities based on the number of protons in the nucleus.	Abundance of different elements and "endangered elements." Impacts of mining and issues of environmental justice. Biogeochemical cycles for elements and their perturbation.
Macroscopic samples of matter contain so many atoms that they are counted in moles.	Molecules can be toxic at even low concentration because Avogadro's number is so large.
Three-dimensional structures give rise to observed chemical and physical properties.	Chirality plays an important role in toxicological properties. Molecular polarity affects the fate of chemicals in the environment.
The physical properties of the state are strongly influenced by the nature of the intermolecular forces.	Water solubility is an important factor in the environmental persistence of a chemical and can be described by the octanol/water partition coefficient (k_{ow}).
In chemical changes, matter is conserved and this is the basis behind the ability to represent chemical change via a balanced chemical equation.	Mass metrics are useful tools to analyze reaction and process efficiency.
Chemical change can be controlled by choices of reactants, reaction conditions or use of catalysts.	The 12 principles of green chemistry can be used to evaluate a chemical process.
The type of energy associated with chemical change may be heat, light, or electrical energy.	Solar cells convert light to electrical energy; increasing their efficiency and reducing cost are active areas of research.
Catalysis increases the rate of reaction and has important applications in a number of subdisciplines of chemistry.	Catalysis plays a key role in increasing the selectivity and efficiency of chemical reactions.

Figure 4-4 **Linking Green and Sustainable Chemistry to Standard Chemistry Topics** (adapted from Holme 2019, page 41)



Mapping of planetary boundaries (green) to rich topics (yellow) that map to traditional, chapter-based content organization for the first semester of general chemistry (blue)

Box 4-5 Green and sustainable chemistry university education in emerging and developing countries

Despite many promising initiatives in countries such as Brazil, China and South Africa, further efforts are needed to scale-up green and sustainable chemistry education in universities and research institutes in developing and emerging economy countries. Obstacles include language barriers, lack of translated material, lack of trained scientists, and pressure to publish which may deter from educational reform (Zuin *et al*. 2021). These challenges may be partly overcome by connecting educators, administrators and students from developing countries with established green and sustainable chemistry initiatives in other regions (Hurst 2019). For example, a partnership between the Universitas Gadjah Mada (UGM) in Indonesia and the German Academic Exchange Service focused on integrating sustainability into university chemistry education in Indonesia. Exchange activities included interviews on the challenges which Indonesian instructors face to implement green chemistry in the classroom, and a university site visit for Indonesian educators to Germany to observe laboratory practices and chemistry lectures (Hamidah *et al*. 2017).

- In Figure 4-4 Holme (2019) presents an example of a semester long introductory chemistry course which uses the biogeochemical flows and climate change concepts featured in the planetary boundary framework (Steffen *et al*. 2015) to infuse green and sustainable chemistry concepts into traditional chemistry education. Given the university's location in an agricultural zone, the course uses the nitrogen cycle to connect the chemistry topic of solubility with toxicology, land use considerations and water quality.

4.3.4 Green and sustainable chemistry in post-bachelor tertiary education

Chemistry education at the graduate level provides a unique opportunity to link interdisciplinary knowledge with advanced green and sustainable chemistry research. Equipped with advanced knowledge and skills, graduate students can influence the direction of research programs and the practices of professional communities. Despite these potential benefits, graduate level green and sustainable chemistry education is still in its infancy, presenting opportunities for up-scaling of existing initiatives and the launching of new programs.

4.3.5 Master's degree programmes in green and sustainable chemistry

At the graduate level, educators often have some degree of freedom in designing curricula. This has led to the development of various innovative green and sustainable chemistry masters programs.

- The MSc programme at the University of York in Green Chemistry and Sustainable Industrial Technology teaches students how green chemistry can address industrial sustainability

Box 4-6 Interdisciplinary Learning through the Greener Solutions Program (UC Berkeley n.d.)

Large universities with many fields of graduate students are perfect settings to leverage interdisciplinary learning that builds the capacity of a variety of students to develop green and sustainable chemistry innovations. At the University of California Berkeley in the USA, the project based greener solutions class partners teams of students from a range of disciplines with companies, NGOs, and/or government agencies that are interested in advancing green and sustainable chemistry.

The goal of these interdisciplinary projects is to understand and characterize the opportunities for the adoption of safer chemicals and materials within the partner organizations. Many of the projects started in this program have grown into larger initiatives at the university or within the partner organizations. Examples of projects can be found at the greener solutions homepage (UC Berkeley n.d.).

challenges. It includes an independent research project conducted with experts in industry (York University 2021).

- In Spain, an interuniversity master's degree in green and sustainable chemistry involves the collaboration of three universities, the Universitat Politècnica de València (UPV), the Universitat Jaume I de Castelló (UJI) and the Universidad de Extremadura (UEx). The curriculum focuses on sustainable chemical processes and provides students with the opportunity to conduct a research project at the Institute of Chemical Technology, a leading public research institute (UPV 2021).

Doctoral programmes in green and sustainable chemistry

Doctoral programs with a focus on green and sustainable chemistry seek to change the direction of advanced academic chemistry research towards sustainability. The promotion of these programs is important due to the key role which doctoral level academic research plays in the ecosystem of innovation for green and sustainable chemistry. The corresponding research outputs can contribute directly to the development of technological innovations that advance advance UNEP's Ten Objectives and Guiding Considerations.

- Various research tracks are available to PhD students at The Environmental Research Institute at the National University of Singapore (NUS) such as "Environmental and Human Health" and "Resource Recovery and Circular Economy" (NUS 2021).
- The Green Chemistry Track PhD Program at the University of Massachusetts in Boston, U.S.A. (UMB) provides students with tools to assess the impact which human chemistry activities have on human health and the environment, preparing students for conventional chemistry jobs in industry, government, and academia. In addition to traditional training in the chemical sciences, the program emphasizes interdisciplinary learning by allowing students to take courses in the Biology Department and the School for the Environment (UMB n.d.).
- Several other universities offer similar PhD programmes, including Sichuan University in China (Wang, Li and He 2018) and the Doctorate in Sustainable Chemistry at the UPV in Spain (UPV n.d.).

Professional schools and curricula

Professional schools and/or graduate programmes in disciplines such as pharmacy, medicine, environmental studies and law are also taking up green and sustainable chemistry topics. Infusing relevant concepts into these educational settings can result in professionals with an awareness of green and sustainable chemistry that affects their habits or goals in the workplace.

Box 4-7 Professional Master in Sustainable Chemistry – Leuphana University (Leuphana University 2021)

A professional Master's in Sustainable Chemistry was developed by Leuphana University in collaboration with the International Sustainable Chemistry Collaborative Centre (ISC3) and debuted in 2020. The wide-ranging curricula looks to inspire systems thinking and provide learners with skills that enable them to contribute to the development of chemistry solutions for sustainability challenges.

Learning topics range from green computational chemistry and toxicology to global product flows and international chemical regulatory frameworks (Leuphana University 2021). The targeted nature of this degree program serves as an example of how to equip students with the tools and knowledge to advance green and sustainable chemistry as professionals in research, industry and government. It may inform development of other green and sustainable chemistry master's programmes through inter-university and organizational partnerships, taking into account regional and local contexts.

Box 4-8 **Preparing doctoral and masters chemistry students for the real world.** The RenewChem graduate training program at the University of York (Summerton *et al.* 2019)

During an event on "Green Careers" organized by the Green Chemistry Centre of Excellence (GCCE) at the University of York in 2015, industry representatives highlighted the need for changes to current graduate level chemistry education. While chemistry knowledge of most of the chemistry graduates was excellent, there was a need to develop additional skills, knowledge, and experience to ensure that future employees of industry can make an impact. The exchanges led to the development of an annual series of workshops for doctoral and master's students. The workshops featured multidisciplinary and multisectoral topics under the theme of "Sustainable Manufacturing for the Chemical Industry". Topics covered include:

- Circular economy
- Resource efficiency
- Regulation
- Triple bottom line concept
- Life cycle thinking (upstream and downstream)
- Measurement/validation
- Case studies on real world products and technologies
- End-of-life issues
- Industry's drivers and constraints
- Analysis and problem-based approaches
- Ability to work in and lead teams
- Enhanced communication skills

The assessment of the workshops documented that learning outcomes benefited both participating students and were appreciated by industry partners (Summerton *et al*. 2019).

- The Brazilian Green Chemistry School at the Federal University of Rio de Jainero offers courses to graduate level students covering chemical safety, green chemistry concepts and local case studies of green products and processes. The courses attract students in a range of disciplines including biologists, pharmacists and engineers (Seidl *et al.* 2015).

- In the field of sustainable healthcare education, the teaching of sustainability topics may provide an entry-point for green and sustainable chemistry learning. In the United Kingdom, the most recent medical education outcome guidelines address how environmental influence and global changes affect health and wellbeing (Tun 2019)

- For a discussion of the latest development in green pharmaceutical education, see the "Special Issue on Education in Green and Sustainable Chemistry and Green and Sustainable Pharmacy: an integrated approach" (Hurst and Clark 2020).

4.4 Innovative green and sustainable chemistry experiments and learning methods

4.4.1 Green and sustainable chemistry laboratory experiments

Benefits of green and sustainable chemistry laboratory experiments for learning

The laboratory serves as a valuable setting for the presentation, elaboration and learning of green and sustainable chemistry concepts. Supplementing classroom teaching with experimental learning provides students with a holistic and practical view of green and sustainable chemistry's potential to advance sustainability. It is also a unique opportunity for students to visualize chemistry's impact on various aspects of society.

A well-designed laboratory course guides students to carefully think through and prepare for the experiments, and to reflect on the obtained results. Sound preparation includes, *inter-alia*, researching the chemicals and the techniques to be used, as well as understanding the context of the experiment.

Guiding themes for green and sustainable chemistry laboratory experiments

A wealth of experimental plans and frameworks exist which strike a balance between traditional chemistry laboratory learning and sustainability-oriented experiments. Drawing upon these, three guiding themes for laboratory experiments are proposed below. These themes link to UNEP's 10 Objectives and are meant to guide educators and students to design their own green and sustainable chemistry laboratory exercises. By considering these different themes, the laboratory can become an unique context in which students practically participate in systems thinking. Each theme is presented below and illustrated by a case study. Additional examples of laboratory activities for green and sustainable chemistry can be found in the Annex.

Box 4-9 Collaborative development of a high school green chemistry curriculum and laboratory experiments in Thailand (Doxsee and Nuntasri 2011)

Many schools, especially those in developing countries, do not have the facilities or the budget to accommodate all students with access to safe and meaningful chemical experimentation. Green and sustainable chemistry laboratory exercises are ideal to overcome these barriers, as they require less safety equipment and can often be conducted without the use of a fume hood.

With these advantages in mind, the University of Oregon and Thai Distance Learning Foundation partnered to design intrinsically safe laboratory exercises, which can be performed on an open bench, to increase accessibility of laboratory learning to Thai students. The re-designed lab exercises allowed for the accommodation of significantly more students in a single room and reduced instructor contact hours down to a manageable level. The partnership resulted in a published set of green chemistry experiments from which students everywhere in the world may benefit (Doxsee and Nuntasri 2011).

Minimize hazardous chemical releases

Theme 1

Experiments characterized by this theme aim to provide students with hands-on experience and knowledge regarding hazardous chemicals and the effects they may have on human health and the environment. The experiment will often use an alternative, non-toxic or sustainable reagent to perform a typical reaction or synthesis. Ideally, an experiment will require that the students carry-out the synthesis or analysis using both the traditional and alternative sustainable techniques, followed by a comparative analysis. This provides an opportunity for students to assess alternatives and identify trade-offs. The teaching of hazardous chemical handling and assessing risks is also included under this theme.

Relevant Green and Sustainable Chemistry Objectives and Guiding Considerations

- Minimizing chemical hazards 1
- Avoiding regrettable substitutions and alternatives 2
- Minimizing chemical releases and pollution 6

Box 4-10 Case Study for Laboratory Theme 1 on Minimizing Chemical Hazards

Minimizing hazardous chemical releases: The case of designing a sunscreen lotion.

In an experimental plan designed by the Molecular Design Research Network (MoDRN) for secondary-level students, two sunscreens, one containing hazardous oxybenzone and the other zinc oxide, are tested for their efficacy at absorbing harmful ultraviolet rays.

The objective of the experiment is to demonstrate that the two sunscreens perform similarly, with one being less toxic. The preparation and reflection elements of the experiment are meant to stimulate an understanding of the hazardous effects of oxybenzone and how sunscreen use contributes to its release into the environment. Importantly, the lesson still requires the students to familiarize themselves with important lab concepts such as measuring volume, dilution, visual observation, spectrum analysis and visual data representation (MoDRN n.d.).

Promote efficient use of resources

Theme 2

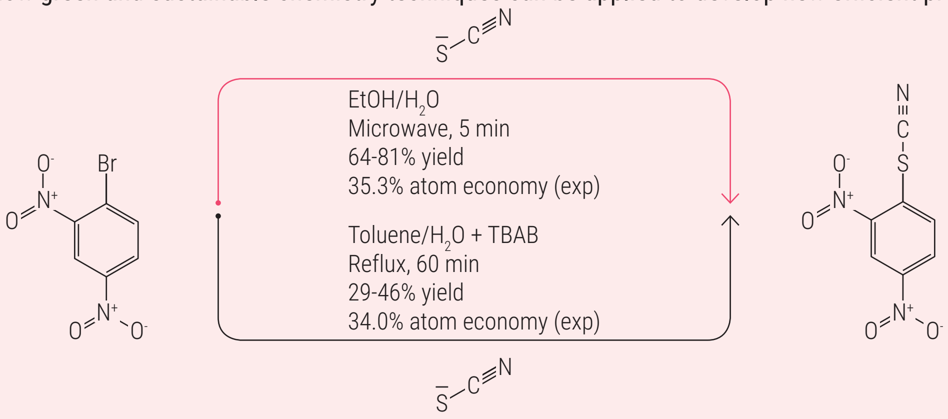
Experiments under this theme demonstrate how resource efficiency can be improved through modifying traditional chemistry processes or by implementing new ones. Here, resource efficiency is used broadly and encompasses reduced use of reagents, improved atomic economy, less waste generation, energy efficiency, increased recycling rates, and circularity promoting processes.

Relevant Green and Sustainable Chemistry Objectives and Guiding Considerations

- Sustainable sourcing of resources and feedstocks 3
- Advancing sustainability of production processes 4
- Advancing sustainability of products 5
- Enabling non-toxic circularity 7

Box 4-11 Case Study for Laboratory Theme 2 on Promoting Efficient Use of Resources

In a comparative laboratory exercise forundergraduate organic chemistry students at the University of Winnipeg in Canada, microwave assisted reactions were compared with classical syntheses. The study demonstrates to the student how microwave heating results in higher yields while requiring less organic solvent and energy when compared to the traditional reflux synthesis technique (Latimer and Wiebe 2015). By leveraging approach 2 the student is encouraged to consider how green and sustainable chemistry techniques can be applied to develop new efficient processes.



Inspire systems thinking

Theme 3

To develop experiments focusing on systems thinking laboratory lessons can be tailored to emphasize the broader implications of chemistry on sustainable development. This is done by providing the student with contextual information for the experiment which stimulates awareness of the interconnectedness of chemistry with social contexts and global systems. Considering larger sustainability challenges in a laboratory context is essential, as it allows students to connect chemistry with societal trends in a practical manner.

Relevant Green and Sustainable Chemistry Objectives and Guiding Considerations

- 8 Maximizing Social Benefits
- 9 Protecting workers, consumers and vulnerable populations
- 10 Developing solutions for sustainability challenges

Box 4-12 Case Study for Laboratory Theme 3 on Inspiring Systems Thinking

Inspire systems thinking: The case of extracting an essential oil from orange peels.

The systems thinking theme is well illustrated through a laboratory exercise designed for chemistry students in the Sao Paulo province of Brazil. The experiment is centered around the extraction of an essential oil from orange peels to demonstrate the chemistry basis for a citrus-based biorefinery. The inclusion of orange peels was deliberate, as Brazil, and in particular the Sao Paulo province, is a world leader in citrus production. To provide greater context to the class, the fact that half of the fruit is discarded as waste was communicated. The authors suggest that using locally relevant examples can enhance a student's sustainable vision and help them to see the potential of chemistry outside of the laboratory (Zuin *et al*. 2019).

Box 4-13 Using all three themes in the laboratory: The case of environmentally benign synthesis of Adipic Acid (Reed and Hutchison 2000)

The environmentally benign synthesis of Adipic Acid was designed at the University of Oregon at a time when few green chemistry concepts were being implemented into the laboratory. This comprehensive experiment is still a benchmark for green chemistry teaching in the undergraduate laboratory today. It is also a good example of how to utilize all three of the above themes in one laboratory activity. Furthermore, the experiment manages to convey critical undergraduate chemistry concepts and techniques such as recrystallization, polymer chemistry, oxidation, and alkene synthesis.

Prior to the experiment, a discussion takes place on the modern industrial production of adipic acid. The current process involves the emission of hazardous by-products, such as the greenhouse gas nitrous oxide and the use of a toxic oxidation reagent, nitric acid. Fostering this discussion is an example of theme 3 in which the student is encouraged to engage in systems thinking by considering the wide-reaching ramifications of a chemical process. Theme 3 could be further emphasized by discussing the dangers which workers at the factory and the communities around the plant face.

Theme 2 is addressed in the experiment through the introduction of a recyclable catalyst. The sodium tungstate catalyst is not consumed in the reaction and can therefore be recovered after carrying out the synthesis of the adipic acid. Here, students can see how green chemistry concepts can be used to minimize waste and create more sustainable processes.

Through using an alternative, non-toxic oxidant and solvent (hydrogen peroxide and water), this experiment leverages theme 1. The substitution of hydrogen peroxide and water for potassium permanganate and an organic solvent respectively is a clear example of green and sustainable chemistry. Learners in the laboratory see first-hand how using green chemistry results in safer conditions and less opportunity for hazardous releases into the environment (Reed and Hutchison 2000)

4.4.2 Alternative and innovative approaches to green and sustainable chemistry learning

Chemistry learning methods are continuously evolving to coincide with the transformation of education towards systems thinking and sustainability. This section presents selected innovative teaching methods and activities that can supplement typical formal green and sustainable chemistry education. Common themes addressed by these approaches include increasing the role of the student, leveraging technological literacy, and promoting learning outside the classroom setting. These alternative learning pathways have the potential to enhance student interest and convey skills in green and sustainable chemistry in ways which traditional learning methods do not.

Fields trips engaging other education institutions

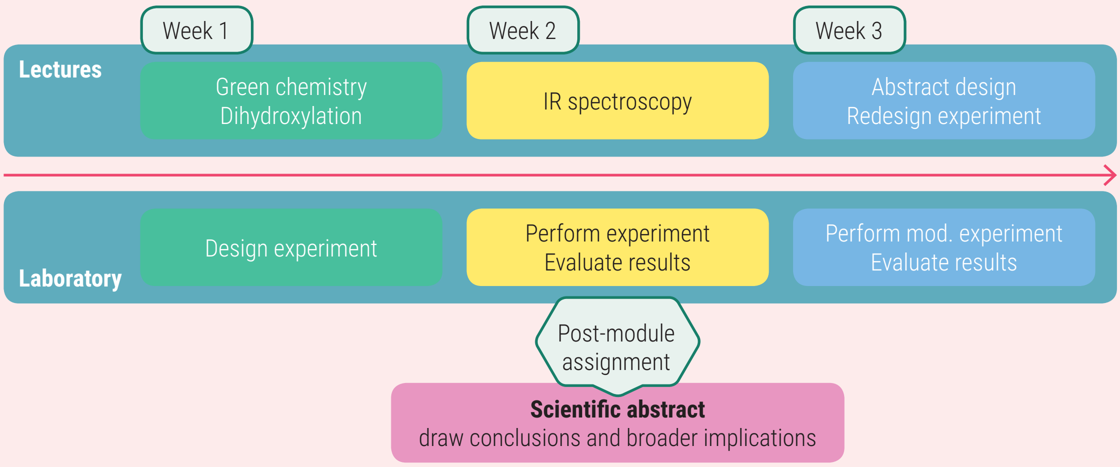
Field trips and excursions are well-known to result in positive changes in attitudes and awareness of students concerning the environment (Farmer, Knapp and Benton 2007).

- In Germany The University of Bremen and Saarland University offered their laboratory facilities to host field trips for secondary level chemistry students to carry out green and sustainable chemistry experiments. The experiments covered topics such as renewable feedstocks, climate change and efficient chemical production. The project provided learning benefits not only for the students, but also for the secondary school and pre-service teachers enrolled at the universities (Garner, Siol and Eilks 2015).
- At Stony Brook University in the United States, day-long field trips were hosted for local secondary school chemistry students in the organic chemistry laboratory to learn about primary chemistry concepts and sustainability topics (Table 4-2). An element of teacher capacity development was also included, by enlisting pre-service teachers to oversee the laboratory activities (Aubrecht *et al.* 2015).

Box 4-14 Developing a student designed laboratory experiment (adapted from Wu *et al*. 2019, page 2)

A model for planning and implementing a student-designed green chemistry experiment was developed for a large-enrollment, introductory organic laboratory course taught at the University of Michigan. Week 1 focuses on student planning of experiment with a greener reaction. In week 2, students execute the experiment. Week 3 provides an opportunity to repeat the experiment and optimize the reaction conditions (e.g. to improve yield). To evaluate student learning and confidence, post-lab writing assignments as well as pre- and post-semester surveys were carried out. The assessment revealed an increase in students' understanding of green chemistry concepts and elevated student confidence to modify a reaction for improved results. The model may therefore inform other large- and small-enrollment laboratory courses (Wu *et al*. 2019).

Scheme 1. Overview of the topics covered in prelab lectures and labs



Another variation is to organize field trips where chemistry students serve as educators. This approach helps to deepen students learning experience and creates mutual benefits.

- As part of their final project for a green chemistry course at Westminster College (United States), students designed and implemented green chemistry experimental plans for students at a nearby secondary school. The projects included experimental plans and pre and post lab questions. The secondary school students reported an increased interest due to the inclusion of green chemistry concepts (Kennedy 2016).

Table 4-2 Learning topics of secondary level education chemistry field trip to a university (adapted from Aubrecht *et al*. 2015, page 2)

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

Table 4-3 **Learning objectives of a community-based learning project for chemistry students** (Dicks *et al.* 2019)

1. To understand the environmental indicators of water quality
2. To be able to link the lecture topics in green chemistry with real-world issues
3. To provide services and information that will benefit Genesee River Watch and the community
4. To become skilled in following protocols of collecting water supplies from a river and analysing them for water quality
5. To develop affective oral and written communication skills through writing reports and presenting results to a broader audience
6. To reflect on the service-learning experience of using one's professional skills to benefit the local community

- At St. Johns Fisher College (United States), university students assisted in the design of a waste to energy unit and introduced the concept to at a local secondary school. Topics covered in the unit included renewable energy, life cycle assessments and waste prevention (Manchanayakage 2013).

Engaging and learning with the local community

Combining chemistry education with community-based learning can increase the appreciation that students have for chemistry studies, benefit the local community all while conveying skills and knowledge related to green and sustainable chemistry (Manchanayakage 2013).

- At St John's Fisher College, a community-based learning project for chemistry students incorporated environmental analysis of a nearby river that linked classroom green chemistry topics with real-world issues. To monitor water quality, the students joined forces with a community based environmental action group. The learning objectives of the project are presented in Table 4-3 (Dicks *et al.* 2019)

Social media content creation for green and sustainable chemistry learning

Considering the high level of social media engagement among young people today, these platforms present an opportunity for formal educators to teach green and sustainable chemistry in a manner that is highly-relevant to their students. Developing content for social media, for example by preparing videos, can be a valuable teaching tool. It gives responsibility to students and motivates them to place green and sustainable chemistry lecture topics into a broader context. Students also gain additional educational benefits such as public engagement and presentation skills, enhanced creativity, and becoming empowered as global educators. Furthermore, the content often ends up being viewed by audiences outside of the formal education system resulting in green and sustainable chemistry learning opportunities for the broader public. University of York in the United Kingdom has pioneered this approach for green and sustainable chemistry with encouraging results, three examples are presented below.

- For a module on polymers taught as part of an undergraduate chemistry course students had the choice to use YouTube (coupled with iTube and weTube) to create and disseminate videos showing the application of chemistry in a real-world context. The students making videos found the experience more enjoyable than students who engaged in the traditional activity of writing articles. The videos remain accessible on the platform and continue to be watched around the world (Smith 2014).
- Undergraduate chemistry students developed a series of educational videos on topics such as circular economy, life-cycle analysis and green chemistry. The videos were placed on a student curated channel on the video-sharing platform Tik-Tok for further dissemination (Hayes *et al.* 2020).
- The popular social-media platform Snapchat was used by students in an introductory

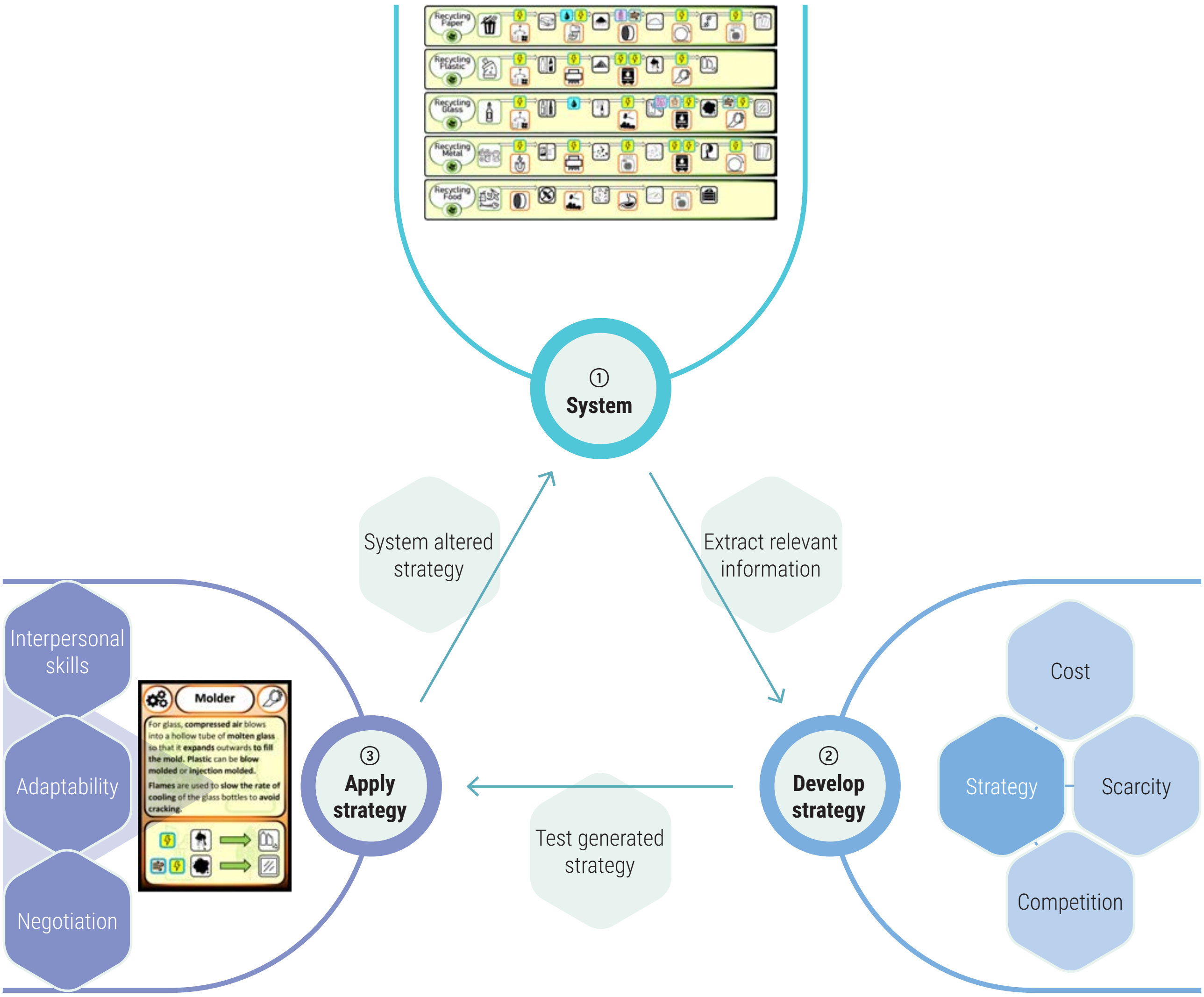
chemistry course to share videos which contextualized what they were learning in the classroom. The majority of the students reported that the Snapchat channel helped them to feel more engaged with chemistry (Hurst 2018).

Games for green and sustainable chemistry learning

Learning through developing and playing games is an approach in formal education which has the potential to motivate students, while providing a situational, learned-centered experience (Arnab *et al.* 2012). A range of games exist that communicate green and sustainable chemistry concepts for students at all stages of formal education.

- Games aimed at younger students include an ACS designed word search containing key green chemistry topics (ACS n.d.) and a matching card game developed by Beyond Benign which encourages students to explore the concept of biomimicry (Beyond Benign n.d.).
- A more advanced card game, called Green machine, was developed as part of a joint effort between University of York in the United Kingdom and University of Augsburg in the United States. The game aims to facilitate systems-thinking and foster an understanding of the UN SDG's by having students compete to establish an operational recycling plant. It has been implemented in undergraduate classrooms to encouraging results (Miller *et al.* 2019).

Figure 4-5 **The Green Machine Card Game** (adapted from Miller *et al.* 2019, page 1)



- The Safer Chemical Design Game conceived by MoDRN is a free online resource for undergraduate and advanced secondary school learners. The game allows students to play the role of a professional chemical designer whose goal is to formulate a functional chemical product with improved human and environmental health impacts (Mellor *et al.* 2018).

- Another digital game "Green Tycoon" is available as a mobile application and introduces students to the bio-refining process model from a green chemistry perspective (Lees *et al.* 2020). The game has been integrated into an undergraduate chemistry course at the University of Augsburg in Germany. Students reported the game to be an engaging and helpful tool for understanding green chemistry's role in sustainable process design (Lees *et al.* 2020).

Two screenshots of the main scene of Green Tycoon. The movement of the truck demonstrated where players tap the truck, instigating a delivery from the refinery (right) to the factory (left). Upon completion, the player earnes money, in this instance £2, and the truck returns from the refinery to the factory, ready tp commence a new delivery.

GREEN AND SUSTAINABLE CHEMISTRY **LEARNING OUTSIDE OF THE FORMAL EDUCATION SYSTEM**

5

Chapter 5 addresses actors responsible for important non-formal and informal educational functions outside of the formal education system. They range from professionals engaged in professional development learning and government officials, to parents educating their children. Chapter 5 therefore covers a range of non-conventional learning opportunities and pathways, such as social media, TV shows and documentaries, and museums. Many of these learning interventions directly target and benefit citizens that play a key role in increasing the market for more sustainable products and shaping political discussions.

Key Chapter Takeaways:

- Learning which takes place outside of the classroom through non-formal and informal education is critical to advance green and sustainable chemistry.
- Non-formal education is especially relevant to professional development and may also complement formal education.
- Fostering an informal learning eco-system for green and sustainable chemistry is key to reach new audiences with various entry-points and relevant examples available.

5.1 What is non-formal and informal education and learning?

5.1.1 Significant learning takes places outside of formal education structures

Learning rarely, if ever, occurs and develops from a single experience. Rather, learning in general, and science learning in particular, is cumulative. It emerges over time through myriad human experiences, including but not limited to experiences in schools, museums, while watching television, reading newspapers and books, conversing with friends and family, and increasingly frequent interactions with the internet.

The experiences children and adults have in these various situations and settings dynamically interact to influence the ways individuals construct knowledge, attitudes, behaviors, and understanding. In this view, learning is an organic, dynamic, never-ending, and holistic phenomenon of constructing personal meaning. This broad view of learning recognizes that much of what people come to know about the world, including the world of science content and processes, derives from a combination of school and real-world experiences in diverse physical and social contexts, motivated by an intrinsic desire to learn. To maximize green and sustainable chemistry learning and assure it reaches all the necessary groups, these settings must be targeted as entry-points for relevant concepts and ideas.

Non-Formal Education

According to UNESCO (2012) non-formal education is an "addition, alternative and/or complement to formal education within the process of lifelong learning of individuals". Non-formal education may engage people of all ages but does not involve a continuous learning pathway. Engaging in non-formal learning is usually the result of an individual's intent to learn, such as mastering a particular activity, skill or area of knowledge. It often takes place through learning that has a short duration, and low intensity, such as short courses, workshops or seminars. Although non-formal learning often takes places outside of the formal education system, the use of organizational frameworks or structure (e.g. learning objectives or exams) is not precluded.

Informal Education

At work, at home or during leisure, individuals are constantly exposed to learning situations. Informal learning can be understood as learning that may occur at home, the workplace, or local community. Informal learning is not institutionalized and therefore much less structured than formal or non-formal education (UNESCO 2012). Oftentimes, it is not intentional. Unintentional or incidental learning takes place as a by-product of participating in an activity, event or communication that is not specifically designed for learning. Examples include learning by engaging in a meeting, by listening to the radio, or watching a television broadcast not designed for educational purposes.

5.2 Strengthening non-formal education to advance green and sustainable chemistry

5.2.1 Professional development activities

Many professionals engaged in chemistry innovation, chemicals and waste management or other chemistry-relevant fields have not received thorough education in green and sustainable chemistry. The backlog of learning is significant and the potential it has to enable professionals in immediately contributing to UNEP's 10 Objectives and Guiding Considerations is high. Scaled-up efforts are therefore needed to fill learning gaps.

To address this challenge, several organizations offer executive and professional green and sustainable chemistry learning resources and activities for mid-career professionals. In addition to these examples, several free, self-standing learning packages aimed at professionals are provided in the Annex.

- The Green Chemistry and Commerce Council (GC3) has developed several professional development webinars and made them available on their website. One on Green

Box 5-1 Train-the-facilitator workshops for green chemistry dissemination (Yale 2019)

A six-part train-the-facilitator workshop series developed by the Global Green Chemistry Initiative and UNIDO aimed to provide a variety of stakeholders with skills and knowledge to become catalysts for green chemistry dissemination in their local communities. The events were held in Brazil, Colombia, Egypt, Serbia, South Africa and Sri Lanka. Each workshop lasted five days and presented case studies on chemical disasters, green chemistry technology topics and implementation strategies. Workshop attendees were strategically chosen as to have the greatest possible impact in their respective communities. For example, at the final workshop in Cairo Egypt, representatives from the Akira Biodiesel production company were present along with government officials in the ministry of trade and environment and several representatives from academic and research institutions around the country (Yale 2019).

Chemistry in Business, targets professionals with a limited understanding of chemistry. It covers topics related to product design, green chemistry market building and supply chain transformation (GC3 n.d.).

- The Toxic Use Reduction Institute (TURI) provides training in reducing hazardous chemical use, resource conservation and environmental management systems. The courses were developed for those interested in becoming certified Toxic Use Reduction Planners but may be taken by anybody (TURI 2021).
- A more structured green and sustainable chemistry learning service is offered to professionals by the University Washington. It helps those working in the chemical space to design safer chemicals and industrial processes. The Green Chemistry & Chemical Stewardship Online Certificate Program targets engineers, supply-chain decision makers, legal professionals and more to communicate the benefits of green chemistry and provide tools to assist in realizing them in the workplace (University of Washington 2021).

Learning by engaging in the greening of institutions

Institutional greening projects present an interesting opportunity for non-formal green and sustainable chemistry learning by allowing individuals to turn ideas into tangible action which affect the environment in which they work, live or learn.

- Eco-Schools, for example is a global initiative in 68 countries that encourages young people to engage with their environment by protecting it. Students start by employing greener practices within their classrooms and proceed to expand practices to the entire school, and eventually their local communities (Eco-schools n.d.).
- The United Arab Emirates' sustainable school initiative was designed to reduce the nation's ecological footprint by facilitating measurement of resource consumption in schools across the nation. The program led to the adoption of new teaching strategies to instill positive changes in student's and citizens behavior (Raghwa n.d.)
- More directly related to green and sustainable chemistry, a partnership between the Department of Environmental and Occupational Health Sciences and the Green

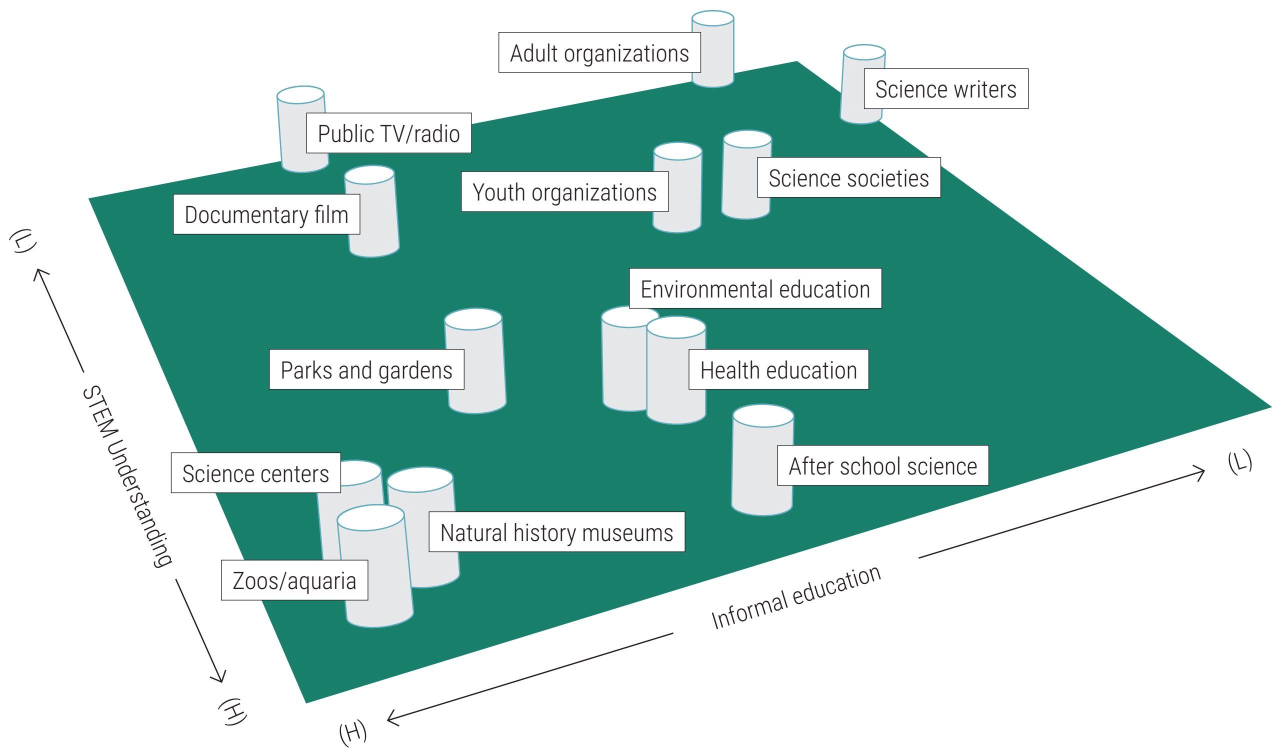
Figure 5-1 **Green Chemistry and Chemical Stewardship Course Flyer** (University of Washington 2021)

Laboratory program at the University of Washington assisted academic laboratories to adopt green chemistry principles and select safer chemicals. Inventories, purchasing records and hazardous waste data were used to evaluate the sustainability of the lab and to select two target chemicals for alternatives assessments (Krenz *et al.* 2016).

5.3 Opportunities for green and sustainable chemistry learning through informal education

Various settings, outlets and opportunities for informal green and sustainable chemistry learning currently exist or are available for further inclusion of relevant concepts. Learning through product labels, social media, books, television, games, in museums and other popular media content is an effective way to inspire interest and awareness in green and sustainable chemistry for a wide range of audiences. These activities may be self-standing green and sustainable learning activities, or they may be placed within broader science, technology, engineering and mathematics (STEM) and sustainability learning initiatives. Certain resources, including the games and social media videos, may have been originally developed through formal learning initiatives but can also play an important role in informal education.

Figure 5-2 The STEM landscape: Opportunities for informal green and sustainable chemistry learning (adapted from Falk, Randol and Dierking 2008, page 11)



Product information, labeling and consumer awareness raising

Providing information on the environmental impact of the products that are available for purchase can result in consumers with knowledge and desire to make choices that advance green and sustainable chemistry. To convey this information, mass communication is needed. It can take different forms: disclosure through legislative frameworks, product information or labelling systems, as well as broader consumer awareness initiatives such as NGO campaigns and digital media.

- Comprehensive regulatory frameworks such as REACH in the European Union strive to make product information available by placing the responsibility on the chemical producer (European Agency for Safety and Health at Work n.d.). Other similar initiatives exist but more effort is required to make this important information available in an accessible and standard manner.

- The All-Ingredient Indication System (AIIS) is a South Korean legislative framework that requires all ingredients employed in the manufacturing of cosmetics be indicated on the label. The legislation was successful in shifting purchasing habits and increasing consumer knowledge. However, it has also been suggested that reading ingredient lists may not be ideal for educating consumers due to lack of context, no information on exposure routes and unanticipated chemical reactions upon use (Lee *et al.* 2020).

Figure 5-3 **Logo for the Sello Ambiental of Colombia** (Ministry of Environment and Sustainable Development of Colombia n.d.)

SELLO AMBIENTAL COLOMBIANO
MINISTERIO DE AMBIENTE Y DESARROLLO SOSTENIBLE

Eco-labeling and related product information campaigns can further aid consumers to make sustainable choices and advance green and sustainable chemistry. Additionally, they are an effective marketing approach for communicating the environmental friendliness of products and are a key tool to support implementation of green public procurement in many developed and developing countries worldwide.

- The EU flower eco-label is based on general environmental aspects and is given to products and services that meet high environmental standards throughout the life cycle (EU ecolabel n.d.)

- Eco-labels may be specific to chemicals as well such as the OEKO-TEX or BLUESIGN certification systems for harmful substances in textiles (OEKO-TEX n.d.) (BLUESIGN n.d.).

- The “Sello Ambiental” is Colombia’s iteration of the eco-label concept. Its evaluation process considers biodegradability, sustainable production metrics and more. For chemical containing cleaning products, receiving the Sello Ambiental requires complying with quantified eco-toxicity levels and avoiding certain chemicals of concern (Ministry of Environment and Sustainable Development of Colombia n.d.).

By facilitating access to information and demanding change, NGOs and trade organizations can raise citizen awareness about the effects and presence of chemicals. These types of initiatives are critical to empower vulnerable populations to both advance green and sustainable chemistry and reap its benefits.

- The Campaign for Safe Cosmetics developed the SkinDeep Cosmetics Database where consumers can explore “online safety profiles” for various cosmetics and personal care products (Bollheimer 2015).

- In Kenya, the iLima NGO targeted women and informal sector workers to raise awareness of toxic chemicals in solvents and cosmetics (International POPs Elimination Network 2012).

- The Association pour la Protection de l'Environnement et Développement Durable de Bizerte (APEDDUB) in Tunisia has held public workshops on harmful chemicals found in children's toys (International POPs Elimination Network 2012).

Social media

Social media platforms such as Facebook, Youtube, LinkedIn and Twitter are critical outlets for promoting informal green and sustainable chemistry learning that reach around the world. They can serve as educational tools through content creation, as well as interaction and exchange. By promoting and following relevant accounts, each moment of social media engagement can become an opportunity for green and sustainable chemistry learning.

- YouTube hosts video content relevant to green and sustainable chemistry, in some cases prepared through formal education, as mentioned in chapter 4. Additionally, the popular page SciShow has over 6.5 million followers and has posted green and sustainable chemistry content such as the video "Sneaky Ways Chemists are Making our World Safer" (SciShow 2021).

- The Facebook page "Chemistry World" with almost 1 million followers recently posted articles on creating clothes from plastic waste and sustainable flow chemistry (Chemistry World n.d.).

- The "Chemistry News" twitter account with 90,000 followers recently posted articles about edible food packaging and new chemistry innovations in solar panels (Chemistry News n.d.).

- LinkedIn, the professional networking social media platform, provides a setting for professionals to share insights and experiences. Several virtual groups exist that foster green and sustainable chemistry exchanges. For example, the Industrial Green Chemistry (2021) group seeks to bring together chemical industry professionals to discuss green chemistry and green engineering. The group Green Chemistry in Drug Discovery (2021)looks to exchange on ideas and methods related to incorporating green chemistry concepts without sacrificing speedy drug discovery. "The Green Chemistry and other Green Developments in Pulp and Paper" (2021) group acts as a forum for sharing sustainable ideas for energy systems, waste management and other green chemistry concepts in the paper industry.

Books and Journalism

Despite the advent of social media, traditional print media and the dissemination activities associated with publication can still act as a useful avenue for promoting green and sustainable chemistry learning and awareness to all audiences. In addition to books, newspapers are included in this category many of which have run articles related to the topic of green and sustainable chemistry.

- A children's book titled "The Green Formula" (Figure 5-4) follows four young scientists on their journey to win a green chemistry science award. The book includes key green chemistry principles and includes a corresponding activity pack with green chemistry experiments (Hurst 2018).

- The book "Count Down" aims to raise awareness in an accessible manner around the urgent issue of endocrine disrupting chemicals in everyday products (Swan and Colino 2022).

- The popular science magazine, Seed, ran an article featuring an interview with Beyond Benign founder Amy Cannon on the benefits of green chemistry (Masciangioli 2011).

Figure 5-4 **Cover of the Green Formula children's book** (Hurst 2018)

- Investigative journalism may also be relevant to green and sustainable chemistry, acting as an important safeguard for public chemical security. The "Trade Secrets Report" was an investigation by journalist Bill Moyers which revealed secrets related to the harmful effects of vinyl chloride which the chemical industry did not intend to release to the public (Rosier 2004).

TV shows, documentaries and radio programmes

TV shows, documentaries, movies and radio programmes can effectively bring attention to both the harmful effects of chemistry and the solutions it offers. These channels are a useful opportunity for viewers to participate in incidental or unintentional learning.

- The popular movie Erin Brockovich is based on a true story chemical release disaster in which chromium leaks into a community's ground water (Rajesh 2020).
- A four-part television series released in 2020 called "The Power of Green Chemistry" shows viewers the potential of chemistry for addressing large-scale sustainability problems (CNBC 2020).
- The documentary, "The Promise of Biomimicry" developed by the Biomimicry Institute, seeks to bring attention to the power of nature-inspired design and highlights innovations which are relevant to green and sustainable chemistry (Biomimicry 2021).
- An interview for the program "This Green Earth" on U.S.A. public radio, discussed green chemistry concepts with Professor Paul Anastas (Yale University 2020).
- The popular science radio show "Earth Sky" enlisted the help of the ACS in finding researchers to interview for a special series on green chemistry. The series was a success resulting in over 58,000,000 radio and internet impressions (Masciangioli 2011).

Museums

Museums are a helpful way to promote interactive, fun learning for kids and adults alike and have great potential to act as settings for informal green and sustainable chemistry learning. Although chemistry is generally underrepresented in exhibitions compared to other sciences, there are

Figure 5-5 **Alternatives Assesments activity at the Koshland Museum** (Masciangioli 2011)

helpful examples of relevant museum initiatives (Domenici 2008). Greater efforts are needed to re-orient the content of science museums to include more sustainability considerations and to expand into other regions through international partnerships.

- A multimedia exhibit previously shown at the Museum of Science in Boston, U.S.A. demonstrated the importance of chemistry for the development of alternative energy sources (PRNewsWire 2010).

- The Koshland Science Museum in Washington D.C., U.S.A. (now closed) was aimed at older teens and adults and contained chemistry learning opportunities in all its exhibits and even touched on the confluence of science and policy (Masciangioli 2011). A relevant aspect was in the climate exhibit, where visitors were led to consider the various economic and environmental tradeoffs for reducing greenhouse gases.

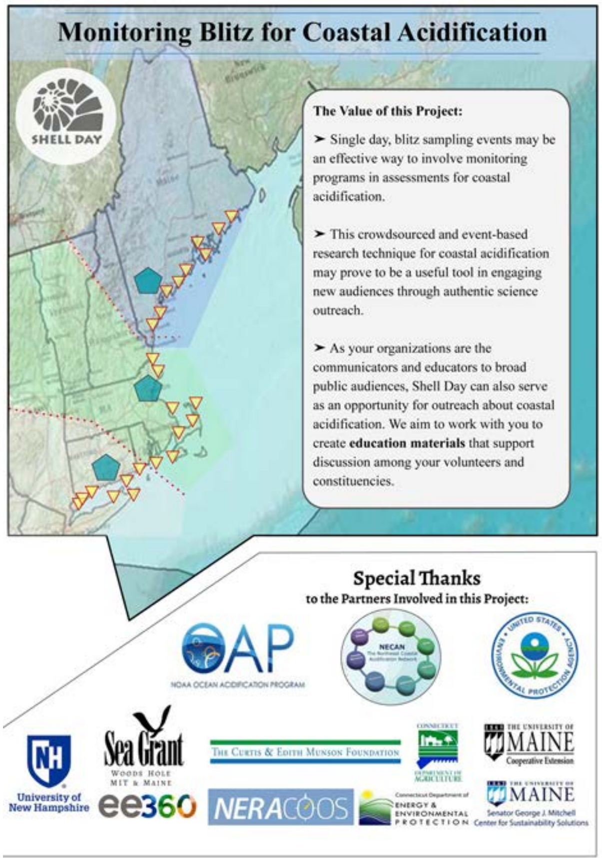
Citizen Science

Citizen science activities in which volunteers engage in environmental monitoring can result in powerful informal learning experiences for green and sustainable chemistry concepts. These initiatives are mutually beneficial as the scientists receive valuable data while citizens gain scientific knowledge and environmental awareness.

- The Organization for the Prohibition for Chemical Weapons deployed chemical sensors to measure air pollution levels around the world. Besides measuring air pollution, the project sought to improve scientific data literacy among the participants and demonstrate chemistry as a driver for change (Mahaffy *et al.* 2017).

- A comprehensive sampling of a carbonate system in an estuary ecosystem was executed via citizen science. The one-day event deemed Shell-day enlisted 59 community science programs and seven research institutions to organize the citizen-led collection of 410 samples from 86 different geographical stations in the northeastern U.S.A. (Rheuban *et al.* 2021).

Figure 5-6 **Shell Day outreach flyer** (Rheuban *et al.* 2021)



STRATEGIC ACTION FOR GREEN AND SUSTAINABLE CHEMISTRY EDUCATION

6

Chapter 6 is presented to change agents that have a central role to play in accelerating transformative change to advance green and sustainable chemistry education. It seeks to encourage and inform planning for strategic action on various scales from the national to organizational levels (e.g. major chemical companies, universities, school-systems). A call is made for the development of roadmaps, with key considerations and examples presented in the chapter. Links are drawn back to earlier parts of the manual in a strategic manner which seeks to turn the manual from advice into action.

Key Chapter Takeaways:

- Strategic action involving collaboration between a wide range of stakeholders is necessary to advance green and sustainable chemistry education.
- Roadmaps are a key tool for strategic action that engages new actors, fosters commitment and generates new educational resources.
- The roadmap development process is unique depending on the organizational context, but there are some universal considerations and steps.

6.1 The time is right to scale up action for green and sustainable chemistry education

The gaps and opportunities presented in this specialized manual point in one direction, without action on education, the UNEP's 10 Objectives and Guiding Considerations for Green and Sustainable Chemistry will not be achieved. Supporting and inspiring action by organizations offering chemistry education is naturally the primary goal of this manual. However, it is equally important that governments, private sector stakeholders, research institutions and other stakeholders take steps to scale-up their efforts to promote green and sustainable chemistry learning. The public sector has a key role to play, by putting in place enabling policies and actions that can foster the required transformation in education. Relevant public sector measures may include providing financial support for green and sustainable chemistry education and research initiatives, promoting curriculum reform in formal education institutes, or supporting educator teaching programs.

Strategic action for green and sustainable chemistry education may take place on its own or within a larger context to advance the concept as a whole. For example, promoting green and sustainable chemistry learning in schools may be one particular aspect of a country's green and sustainable chemistry plan. Emphasizing gender inclusivity in strategic action efforts is key to achieving impacts that advance all of UNEP's Ten Objectives. Whichever approach is taken, it is essential that action be of a collaborative nature. Involving a wide range of actors and facilitating experience sharing is key to create the transformative shift to green and sustainable chemistry.

The 2030 Sustainable Development Agenda is a useful framework and can be an important driver to mobilize the needed commitment to bring all relevant actors together. As a universal global framework endorsed by countries and stakeholders, many of its 17 SDGs and their specific targets directly or indirectly target chemistry innovation and education.

6.2 Developing strategic road maps to advance green and sustainable chemistry education

Roadmaps are an extremely useful tool to coordinate planning for the implementation of green and sustainable chemistry education and raise the profile of strategic efforts. The roadmap approach for planning and decision-making has been used for many years, especially in the area of technology innovation. It is a technique which brings actors and stakeholders together to develop a common vision and a long-term plan to achieve it. Beyond identifying a common vision, roadmaps help to identify existing resources, describe gaps, define actions, and help to obtain funding to fill the identified gaps. They are often used in the private sector, but are equally relevant for other stakeholder groups, including public bodies.

Given the potential benefits of road maps, the GCO-II (UNEP 2019) as well as UNEP's Green and Sustainable Chemistry Framework Manual (UNEP 2020) encourage the development of country- and stakeholder-driven roadmaps. Road maps can support the global implementation of the sound management of chemicals and waste beyond 2020 and help monitor progress both at the organizational, national, and global levels (UNEP 2019). Green and sustainable chemistry education roadmaps therefore do not only advance local and organizational objectives but also make a distinct contribution to global efforts to achieve the sound management of chemicals and waste, as called for at the highest political level by the UN.

Green and sustainable chemistry education road maps may be developed by diverse stakeholder groups (e.g. education institutions, NGOs, corporations, research institutions, the public sector) to advance concerted action. Or they may be developed for specific topics or themes (e.g. advancing formal green or sustainable chemistry at the national level). If prepared at the national level, they may set specific national goals and targets relevant for policy making. What is required is sound leadership within the relevant institutions and organizations. Such leadership can come from the top through senior management or policymakers, or from the bottom up through interested and committed individuals from all stakeholder groups.

6.2.1 Examples of strategic initiatives to advance green and sustainable chemistry education.

A number of actors and institutions have already initiated formal or semi-formal process with the goal to advance green and sustainable chemistry education. Although not necessarily referred to as road maps, these processes do contribute to forming a strategic approach towards scaling up green and sustainable chemistry education. Examples of strategic initiatives, - in some cases also referred to earlier in the manual, - include:

- The ACS Green Chemistry Institute's Green and Sustainable Chemistry Education Road Map (ACS n.d.)
- The Green Chemistry Network Centre (GCNC) at Delhi University (with the support of IUPAC) (GCNC n.d.)
- The Green Chemistry Initiative at the University of Toronto (University of Toronto n.d.)
- Green Chemistry Centre of Excellence Initiative at the University of York (University of York n.d.)
- The Chemical Management Plan of Curtin University (2019)

6.3 Considerations and questions to guide planning for strategic action to advance green and sustainable chemistry learning

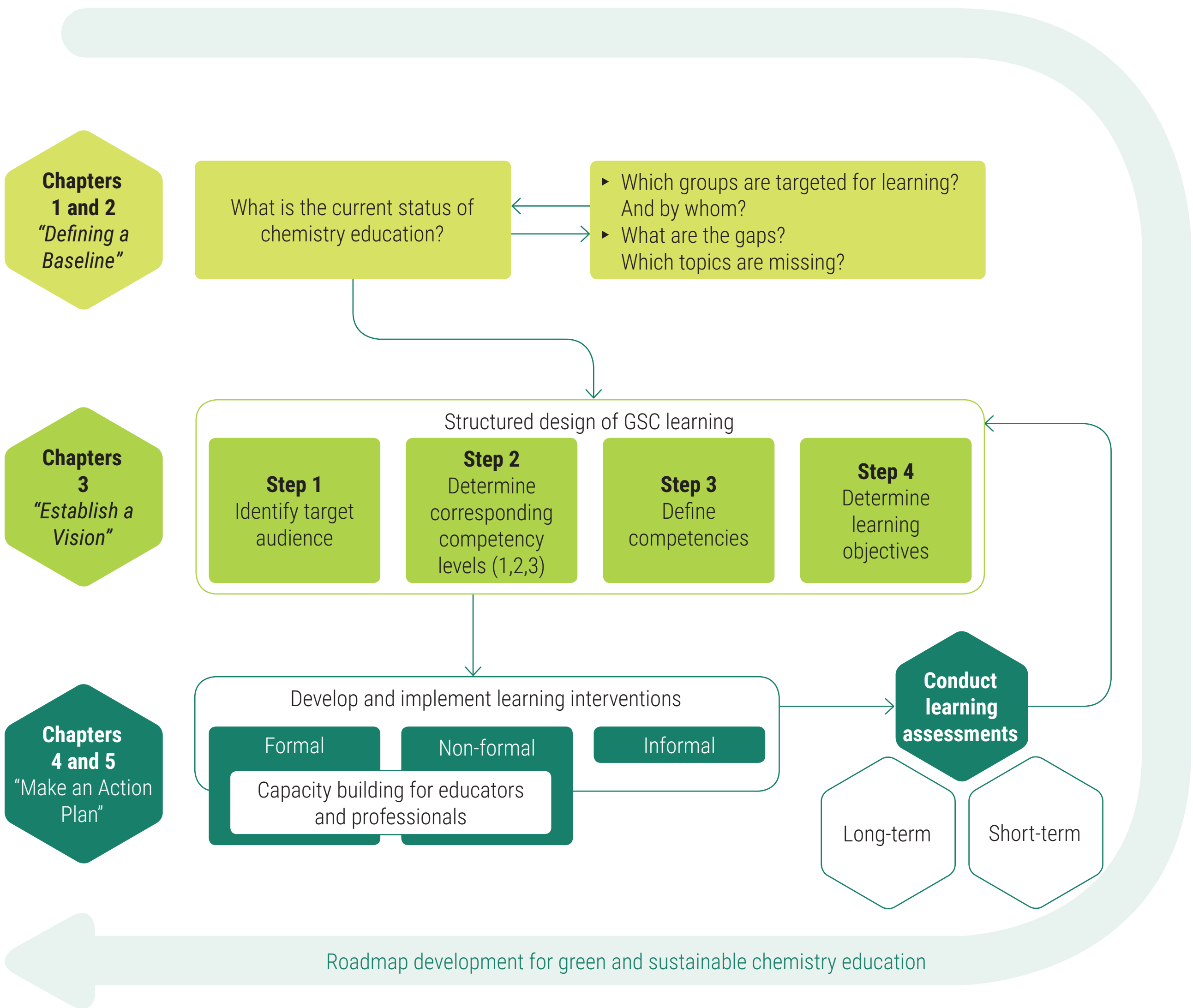
Planning for strategic action to advance green and sustainable chemistry learning is specific to a given context or organization. Common to all situations though is their end-goal of fostering change. No matter the level at which a roadmap is developed, common questions arise. This final section of the manual introduces a set of questions which organizations and actors engaged in road mapping or strategic action on green and sustainable chemistry education may want to consider during the process. For many of these questions, previous sections of the manual provide an introductory discussion and refer to specific resources available. Therefore, cross-checking with earlier parts of the manual is encouraged.

Figure 6-1 illustrates how the chapters of this specialized manual can inform the road map development process. The questions below provide additional guidance with the manual containing information and resources which may help to answer them.

6.3.1 Assessing the current situation and defining a baseline

- To what extent do current practices in the organization embrace and support green and sustainable chemistry learning?
- If there is a lack of support; What are the reasons and possible root causes? (e.g. awareness, concerns, funding constraints)?
- What are the gaps that currently impede effective green and sustainable chemistry learning in the organization?

Figure 6-1 **Roadmap Development Guiding Diagram**



- Who needs to be involved with the roadmap development process to ensure it is inclusive and to maximize future uptake?
- Who are the key stakeholders within the organization shaping educational activities related to chemistry?

6.3.2 Developing a vision and scope for the road map

- What should be the vision for the green and sustainable chemistry education roadmap and its proposed interventions?
- How ambitious should the vision be?

Figure 6-2 **American Chemistry Society Green and Sustainable Chemistry Education Road Map Vision** (adapted from MacKellar *et al*. 2020)

Road Map Vision

"Chemistry education that equips and inspires chemists to help solve the grand challenge of sustainability"

This vision anticipates a **multifunctional future state** encompassing the following:

The practice of chemistry changes...

From: Chemistry is focused on academic and economic value with minimal regard for environmental, safety or health impacts.	→	**To:** Process and product design to minimize adverse environmental, safety, and health impacts while enhancing desired performance throughout the product life cycle.

The "pull" of demand for green chemistry changes...

From: Green chemistry is seen as having little substantive benefit, while costing more to implement than its return on investment.	→	**To:** Green chemistry is inseparable from routine chemistry practice and is recognized for its pivotal role in advancing sustainability and commercial success.

Green chemistry core competencies...

From: Chemistry graduates are fully conversant in the terminology, strategy, and tactics of traditional principles, yet largely isolated from outcomes related to sustainability.	→	**To:** Chemistry graduates leverage green chemistry strategies and tools to develop and apply novel, sustainable chemicals, chemistries, processes, and products.

Chemistry education and academic enterprise...

From: Green chemistry concepts are supplemental to core course work and there is a poor understanding of how to reduce chemical hazards and risks.	→	**To:** Faculty are well-versed in and infuse green chemistry concepts in the teaching and research training activities at all levels, including academic research.

Achieving this vision is important because it will help to move us toward a more sustainable human enterprise that preserves economic vitality and human and environmental well-being. Achieving this vision will help chemistry to be seen as vital to any comprehensive sustainability strategy and a source of pride as it moves to the front lines of the campaign toward a more sustainable world.

This vision will be achieved through the best science, using evidence-based practices and interdisciplinary approaches.

- What should be the timelines be for achieving the various aspects of the vision? (e.g. By 2025)
- How can the vision be linked to international developments and goals? (e.g. the SDGs, UNEP's 10 Objectives and Guiding Considerations for Green and Sustainable Chemistry, etc.)?

6.3.3 Identifying the main target group(s) and beneficiaries *(see also chapter 3, section 3.1)*

- Who is (are) the main target audience(s) which the roadmap seeks to address?
- Why is enhanced green and sustainable chemistry education important for each target audience?
- How will the target groups apply their learning about green and sustainable chemistry?
- Does the integration of green and sustainable chemistry learning carry any potential risks for the target groups?

6.3.4 Identifying competencies, learning needs and road map actions *(see also chapter 3, sections 3.2 to 3.5)*

- What competencies and learning outcomes are envisioned for the identified targets audience(s)?
- What is the nature of the target group's learning needs, i.e., what are possible gaps in knowledge, skills, and attitude?
- Which green and sustainable chemistry learning topics are important to communicate?
- Are any more formal changes in curricula/training foreseen? What are the challenges that need to be overcome to make these changes?
- Is there existing capacity to implement the proposed action? Are capacity development activities needed (e.g. for educators)?
- What potential obstacles need to be addressed early on?

6.3.5 Designing learning interventions to achieve proposed objectives *(see also chapters 4 and 5)*

- What learning activities/interventions are best suited to address the identified gaps?
- For formal learning activities, what resources can be used to help with the design of classroom activities?
- What laboratory activities can be included to further green and sustainable chemistry learning in the classroom?
- Which innovative learning methods could be employed for formal education target audiences? (Games, social media, field trips)
- Is it possible to leverage non-formal learning activities to achieve the proposed learning objectives?
- How would creating an eco-system of informal green and sustainable chemistry learning progress the objectives of the roadmap?

6.3.6 dentifying key actors and determinants to make it happen.

- Who should take the lead in taking the identified actions forward?
- Who are the actors within the organization needed to provide enabling support? How can they be made aware of the need for their support?
- Which actors outside the organization and/or potential partners may be able to provide additional support?

6.3.7 Adopting, implementing and reviewing the road map

- Will the road map be formally adopted? If so, by whom?
- Will there be a public event to announce the road map?
- What supportive communication efforts are needed to generate momentum?
- How will be implementation of the road map be monitored and reviewed? Will an evaluation take place at a certain point in time to assess success, impacts and make adjustments?

ANNEX

Topical and general resources for Green and Sustainable Chemistry Learning

General Resources – Textbooks, academic publications, special journal issues

Several educational textbooks and academic publications are available that cover diverse scientific and technology topics relevant for green and sustainable chemistry. For example:

- "Green Chemistry: Theory and Practice"(Anastas and Warner 2000) provides an overview of green chemistry topics. It is the first of its kind, and widely used in green chemistry teaching.
- "Advanced Green Chemistry" is a series of two textbooks with part 1 encompassing Greener Organic Reactions and Processes and part 2 titled "From Catalysis to Chemistry Frontiers" (Horváth and Malacria 2018)
- "Periodic Table of the Elements of Green and Sustainable Chemistry" (Zimmerman and Anastas 2020) expands upon green chemistry concepts to include a broader set of topics relevant to the sustainable development.

Books and special journal issues focusing on green and sustainable chemistry education include:

- "Worldwide Trends in Green Chemistry Education" (Zuin and Mammino 2015)presents green chemistry education initiatives from around the world, including those taking place in developing and emerging countries.
- "Integrating Green and Sustainable Chemistry Principles into Education" (Dicks and Bastin 2019) features examples of courses and initiatives mainly drawing from trends in North America, with some international examples.
- "Chemistry Education for a Sustainable Society"(Obare, Middlecamp and Peterman 2021) is a two-volume series: Volume 1: High School, Outreach, & Global Perspectives and Volume 2: Innovations in Undergraduate Curricula.

Organizations offering access to courses and learning resources

- Beyond Benign's website features educational resources to empower educators, students and the community to practice sustainability through chemistry. The organization works with educators and a network of strategic partners, covering an educational continuum from K-12 to higher education, as well as community engagement (Beyond Benign 2021).
- The UNIDO Green Chemistry Tool Kit features introductory and advanced green chemistry training courses, as well as materials, cases studies, videos and links to further resources. The aim of the Tool Kit is to transform learners into green chemistry facilitators who will disseminate green chemistry knowledge within their institutions and networks(UNIDO 2020).
- The UNEP Eco-innovation Manual, specifically its chemicals supplement, provides business actors with step-by-step guidance towards the implementation of implementing sustainable chemical business models (UNEP 2017).
- The Innovative Approaches for the Sound Management of Chemicals and Chemical Waste (IAMC), Toolkit is aimed at industry professionals. It provides an overview of green chemistry and chemical process improvement techniques, hazardous chemical identification and substitution, manufacturing best practices, resource efficiency methods and emission reducing processes (IAMC 2017).

Resources for complementary, essential learning topics for green and sustainable chemistry education

Toxicology and eco-toxicology

- The Beyond Benign website features access to a toxicology curriculum database containing lesson plans and laboratory experiments. They also offer a webinar on toxicology in the chemistry curriculum, various symposia and workshops, and past presentations(Beyond Benign n.d.).

- Learning Toxicology through Open Educational Resources is a free online platform to deliver and share knowledge and skills related to the field of toxicology. Its aim is to improve access to learning in toxicology while promoting active learning and virtual and blended mobility (Learning toxicology through open educational resources n.d.).

- The MoDRN network has developed toxicology learning modules for university students containing assignments, background information, corresponding learning outcomes and videos. Various toxicology concepts and examples are covered in the modules and are related to computational chemistry tools used for toxicology screening during chemical design (MoDRN n.d.).

- As part of their "Greening Across Chemistry Curriculum" initiative, The University of Scranton has developed a classroom lesson plan on toxicology in English, Portuguese and Spanish. The module uses insecticides as a case study to communicate key concepts of toxicology and how this information can be used as a tool to develop safer chemicals (Foley n.d.).

Chemical hazard assessment and classification of chemicals

- The United Nations Institute of Training and Research (UNITAR) has developed a professional e-learning course on the implementation of the GHS which is run twice yearly. Links to other educational resources related to the GHS are also provided (UNITAR n.d.).

- The European Chemical Agency (ECHA) offers online training on analysis of alternatives intended for those working in government, industry and NGOs (ECHA n.d.).

- The OECD's toolbox on substitution and alternatives assessment is a compilation of resources, case-studies and accessible data to help with learning related to chemical hazard assessment and alternatives assessments (OECD n.d.).

Sustainability and life cycle assessment

- A free set of e-learning courses in various languages has been developed by the Life Cycle Initiative. They address life cycle thinking from different perspectives with modules related to product design, value chain assessment and public policy applications (Life Cycle Initiative n.d.).

- The International Life Cycle Data System (ILCD) has developed a general guide for life cycle assessment which targets industry professionals and post-graduate students. It contains a comprehensive overview of life cycle thinking along with a cookbook style guide for conducting a life cycle analysis (ILCD 2010).

- OECD has published a document called "Guidance on Key Considerations for the Identification and Selection of Safer Chemical Alternatives" which includes substantive content related to life-cycle analysis (OECD 2021).

- A collection of resources collated by the "STEM Learning" organization provides educators of younger students with lesson plans, activities and case studies to teach the basics of life cycle assessment and analysis (STEM Learning n.d.).

Material and product design for sustainability and circularity

- The Sustainability Guide developed by EcoDesign Circle supports designers to create innovative products, services, processes, systems, or environments to meet future sustainability requirements (EcoDesign Circle n.d.).

- The European Environment Agency (EEA) describes a practical step by step approach to design safe and sustainable products by identifying enabling conditions, challenges and opportunities (EEA 2021).

- Two free courses developed by the Delft University of Technology (DELFTU) are hosted on the EdX platform and introduce sustainable product design for circularity. The first course offers an overview of circular economies and how product design can contribute to them. The second course delves into the specifics behind circular product design using the Design for R strategies: reuse, repair, remanufacturing and recycling (DELFTU n.d.).

- The Circular Classroom has developed an interactive educational toolkit for upper secondary high school educators and students to integrate circular thinking into the classroom(The Circular Classroom n.d.).

- The Ellen Macarthur Foundation has developed a compilation of online courses related to a circular economy (Ellen Macarthur Foundation n.d.).

Systems thinking, SDGs and sustainability.

- The official UN SDG website and its section on student resources provides a wealth of learning resources relevant for inserting the 2030 Agenda into chemistry teaching(United Nations n.d.).

- Publications highlighting the potential role of chemistry to advance sustainable development objectives include; those of SusChem (n.d.), "The Chemical Sector SDG Roadmap" by the World Business Council for Sustainable Development (2018) , A special issue in Current Opinion on Green and Sustainable Chemistry titled "UN SDGs: How can Sustainable Chemistry Contribute?" (SDG Resource Centre 2018); Various resources developed by members of Chemists for Sustainability (C4S) and the International Organization for Chemical Sciences in Development (IOCD) (Hopf *et al.* 2015)

- A module developed by Learning for a Sustainable Future (LfS) aimed at secondary school students uses four lessons focused on different chemistry technology innovations to show the importance of chemistry as a tool for sustainable development. Mainly through addressing climate change and product toxicity (LfS n.d.)

Policy and regulatory frameworks

- The UN Information Portal on Multilateral Environmental Agreements (InforMEA) features publicly available e-learning courses about international chemicals and waste conventions, including the Rotterdam Convention, the Stockholm Convention, the Basel Convention, and the Minamata Conventions (InforMEA n.d.).

- The University of Helsinki of Finland offers a collection of lectures related to the chemical regulatory landscape as they apply to various sectors. The recorded lessons cover topics related to REACH, Safety Data sheets, chemical storage and more (University of Helsinki n.d.).

- The Manual on Compliance and Enforcement of MEAs developed by UNEP is a comprehensive report containing case studies, guidelines and explanatory text related to specific MEAs including those which cover chemicals and pollution (UNEP 2006).

Advanced competencies for green and sustainable chemistry education

Capability to shape chemistry innovation to address sustainability challenges.

Learners will understand the relationship between chemistry and sustainability and are able to develop/recognize chemistry-related opportunities and solutions which harness interdisciplinary collaboration to advance sustainability from a system-wide point of view.

The fourth core competency area focuses on broader "Sustainability Challenges and Opportunities" using a systems thinking approach. It captures the inter-connectedness of ecological, social and economic systems and how they are affected by chemistry activities. It also involves an understanding of the contribution chemistry can make to address sustainability challenges, without creating negative impacts. For citizens, this means obtaining an understanding of broader sustainability challenges, in particular those created by chemicals. It also means understanding how green and sustainable chemistry may contribute to sustainability. For academic sustainability learning, this entails enabling students to plan, conduct, and engage in sustainability research and to build capacity to develop chemistry-based solutions for sustainability challenges. Under this competency, students are able to perform analyses across temporal and spatial scales and consider the implications of actions on other stakeholders (Wiek *et al.* 2011). In summary, students with a proficiency in this competency should be able to consider the impact that any chemistry action may have, with the objective of promoting an economically, socially and environmentally sustainable future for our planet and for present and future generations (Rio Conference, 2012).

- Ability to collectively analyze complex systems across different domains (society, environment, economy, etc.) and across different scales (local to global), thereby considering cascading effects, inertia, feedback loops and other systemic features related to sustainability issues and sustainability problem-solving frameworks.

- Ability to collectively analyze, evaluate, and craft rich ''pictures'' of the future related to sustainability issues and sustainability problem-solving frameworks.

- Ability to collectively map, specify, apply, reconcile, and negotiate sustainability values, principles, goals, and targets.

- Ability to collectively design and implement interventions, transitions, and transformative governance strategies toward sustainability.

- Ability to motivate, enable, and facilitate collaborative and participatory sustainability research and problem solving

Capability to design chemicals with improved sustainability performance.

Learners will understand chemical hazards and are able to design, select, or choose chemicals (or products containing chemicals) with improved sustainability performance across the life cycle.

The first competency focuses on advancing "Sustainable Chemicals". It covers abilities needed to advance the discovery, evaluation, and selection of new and existing chemicals with improved sustainability performance throughout the life cycle, while performing desired functions. This competency area involves using tools and methods that distinguish benefits and drawbacks of specific chemicals. While mainly relevant for advanced students and professionals, this core competency area is also relevant for other groups.

- Ability to collect, analyze, evaluate the quality of, interpret, and compare data that can be used to select/design new chemicals/materials or chemical/ material alternatives with enhanced function and reduced environmental, health, and safety impacts.
- Ability to use life cycle thinking to reduce the environmental footprint of chemicals and design chemicals and materials for sustainability.
- Valuing collaboration and seeking expert multidisciplinary consultation with toxicologists, ecotoxicologists, engineers, ecologists, biogeographers, and environmental chemists, etc.
- Ability to use decision-making knowledge and tools to understand, evaluate, and compare tradeoffs to optimize the impact–benefit ratio of chemicals from a life cycle and systems perspective.

Capability to design chemical process with improved sustainability performance

Learners will understand that chemicals and materials are prepared through the transformation raw materials via synthetic pathways and chemical processing units. They will be able to design, select or recognize more sustainable chemical processes with greater resource efficiency and minimized releases of pollutants and other adverse impacts.

The second competency area focuses on "Sustainable Processes". It covers the discovery, selection and promotion of synthetic pathways and chemical processes which improve the sustainability and safety of production for both existing and new chemicals and materials. It also encompasses the ability to use tools and methods to identify, evaluate, select, and optimize pathways and processes. For chemists and chemical engineers, this means the selection or design of a sustainable, optimized process to make a desired molecule or material through the systematic identification and life cycle evaluation of potential pathways. Under this competency, chemists and chemical engineers should also have the ability to acknowledge and evaluate trade-offs associated with alternative processes.

- Ability to select more sustainable chemicals, materials, reagents, and solvents, etc., that can be used in the design and optimization of new greener transformations or when improving existing syntheses.
- Ability to select optimal pathways to desired chemicals and materials that maximize sustainability benefits.
- Ability able to take optimized synthetic pathways and evaluate manufacturing processes that maximize sustainability benefits.

- Ability to use decision-making knowledge and tools to understand, evaluate, and compare tradeoffs that will enable them to optimize the impact– benefit ratio of manufacturing from a life cycle and systems perspective.

Capability to design products with minimized sustainability impacts

Learners will understand how chemicals can be used and integrated into products to achieve the best benefit to customers while minimizing life cycle sustainability impacts. They will be able to use this knowledge to design, select or promote products which are safer, and more sustainable from a life-cycle perspective.

The third competency focuses on "Sustainable Products" and their chemistry dimension. It recognizes that chemicals chosen to perform a specific function (or confer desired performance attributes) in a product should be selected with product life cycle impacts in mind. This competency widens the system perspective beyond chemistry, by fostering a broader understanding of sustainability considerations across the life cycle of products. For consumers this could mean being aware of the impact a product choice may have on health or the environment, at all stages of the value chain of the product (extraction and materials inputs, production, use and end of life). This competency area is essential to ensure alternative products are designed using chemicals and materials with minimized environmental and human health impacts. For chemists, this competency means to learn more about the importance of product design, an interdisciplinary topic generally not addressed within the domain of chemistry.

- Ability to effectively integrate chemical and materials data and information into greener product design.
- Ability to design for product function and performance while minimizing environmental, safety, and health impacts.
- Ability to understand and apply life cycle thinking for greener product design.
- Ability to use decision-making knowledge and tools to understand, evaluate, and compare tradeoffs in order to improve the impact–benefit ratio of products from a life cycle and systems perspective.

Additional resources relevant to promoting green and sustainable chemistry learning

Green and sustainable chemistry curricula development resources

- Yale University has designed a curriculum for an introductory university green chemistry course. It contains a syllabus, eight lectures and an exam to teach fundamental chemistry principles and their connection with human and environmental health issues (Ferreira 2021).
- The University of British Columbia green and sustainable chemistry curriculum (mentioned in chapter 2) uses guided inquiry activities to link general chemistry concepts to the UN SDG's (Petillion, Freeman and McNeil 2019).

- The ACS's "Green Chemistry in the Curriculum" publication provides a range of activities and frameworks for specific chemistry subdisciplines (ACS 2018).

Resources for capacity-development of educators

- The UNIDO Green Chemistry Tool Kit supports educators in becoming champions in green and sustainable chemistry education (UNIDO 2020).
- The IUPAC designed online course for secondary school teachers "Introduction to Green and Sustainable Chemistry" (Box 4-1), equips teachers to inspire systems-thinking among students and include green and sustainable chemistry in their curricula (Zuin *et al.* 2021).

Resources for secondary-level green and sustainable chemistry education

- Beyond Benign has developed an entire secondary school curriculum which teaches foundational chemistry concepts through a sustainable lens, while engaging students in systems-thinking (Beyond Benign 2017).
- MoDRN offers comprehensive teacher's modules for secondary school chemistry, biology, and environmental science classrooms to introduce concepts of green chemistry, sustainable chemical design and environmental justice (MoDRN n.d.).
- The Blossom Project hosted by the Massachusetts Institute of Technology (MIT) in the United States has developed lesson plans, projects and videos geared towards teaching secondary students the power of green chemistry with a focus on product design and life cycle evaluations (MIT 2018).

Additional green and sustainable chemistry laboratory experiments

Experiment	Foundational Chemistry Concepts	Green and Sustainable Chemistry Concepts	Source
	Primary School		
Blue Mussel Inspired Adhesives	Hypothesis Testing, Experimental Design	Biomimicry, Alternative Assesments	Beyond Benign
Phosphates versus Non-Phosphate Cleaning Products	Chemical Analysis, Measuring	Systems thinking, Toxicology	ACS
Biodegradable Packing Peanuts versus Petroleum Packing Peanuts	Experimental Design, Solvent Chemistry	Life cycle assessment, Circularity	ACS
Desalination Design	Data Analysis, Separation Methods	Systems thinking, resources efficiency	Beyond Benign
	Secondary School		
Sunscreen Comparison	Dilution, Spectrophotemetry, Data Analysis	Toxicology, Sustainable Product Design	MoDRN
FUEL CELLS: ENERGY FROM GASES INSTEAD OF GASOLINE	Reduction-Oxidation, Electrochemistry	Energy Efficiency, Minizming Pollution Releases	ACS
Teaching Biodiesel	Reaction Equations, Material Properties	Energy Efficiency, Tradeoffs, Renewable feedstocks	Eilks, 1999

University			
Experiment	**Foundational Chemistry Concepts**	**Green and Sustainable Chemistry Concepts**	**Source**
Valorization of Sour Milk to Bioplastics	Acid-Base Chemistry, Polymerization	Circularity, Non-toxic alternatives	Jefferson, 2020
Citrus Based Biorefinery - Steam extraction with orange peels	Distillation, Chemical analysis, Separation	Renewable feedstock, process innovations, systems-thinking	Zuin, 2019
Green Oxidation of Benzyl Alcohol to Benzylaldehyde	Reduction-Oxidation, Catalysis	Waste Reduction, Solvent Replacement, Non-toxic alternatives	Assor, Levy
Microwave Assisted Substitution Reactions	Organic Synthesis, Recrystallization, Analysis	Sustainable Processes, Waste Reduction, Energy Efficiency	Latimer, Wiebe, 2015
Preparation of Gold Nanoparticles Using Tea	Nanotechnology, Sprectroscopy,	Sustainable Processes, Non-Toxic Alternatives, Biomimicry	Sharma, Gulati, 2012

Green and sustainable chemistry learning resources for professionals

- UNIDO's Green Chemistry Toolkit contains one- and four-day intensive training courses to build awareness and encourage implementation of green chemistry by company personnel (UNIDO 2020) (UNIDO 2020).
- As part IAMC toolkit, the Green Chemistry and Chemical Process Improvement Package provides an overview of key process improvement techniques. The package is addressed to consultants working with chemical producers and formulators along with industrial users of chemicals (IAMC 2017).

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science.chemicals@un.org
www.unep.org

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