



Advances in Chemistry Education Series

Chemistry Education for a Sustainable Future

Edited by Catherine H. Middlecamp, Mary M. Kirchhoff,
Peter Mahaffy and Klaus Kümmerer

Chemistry Education for a Sustainable Future

Advances in Chemistry Education Series

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Chemistry Education for a Sustainable Future

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Foreword

From climate change to resource depletion, the role of chemistry in building a sustainable future has never been more critical. Chemistry is not just the science of matter; it is the science of our world. It offers the tools and understanding necessary to address the complex problems that threaten the health of our planet and its inhabitants. As educators, our responsibility extends beyond imparting knowledge; we must inspire the next generation of scientists and citizens to think critically, act responsibly, and innovate sustainably.

This book, **Chemistry Education for a Sustainable Future**, is a timely and essential resource for chemistry educators who seek to improve their teaching practices. The chapters in this volume provide a comprehensive guide for integrating sustainability into chemistry education, offering practical strategies and insights that will help educators at all levels—from introductory courses to advanced research settings—embed crucial concepts into their curriculum.

The journey begins with an exploration of the intrinsic connection between chemistry and sustainability. The opening chapter lays the foundation by illustrating how these two fields intersect and the benefits of incorporating sustainability into the chemistry curriculum. This connection is not merely academic; rather, it equips students to become informed professionals and responsible citizens, capable of contributing positively to their communities and the broader world.

As the book progresses, it delves more deeply into the chemical basis of sustainability, presenting a systems-based perspective that is essential for understanding the impact of human activities on planetary health. Chapters on sustainability tools, such as systems thinking and impact-based metrics, offer educators practical approaches to teaching these concepts, enabling students to engage meaningfully with the material and apply their knowledge to real-world challenges.

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The inclusion of sustainability frameworks, such as the Planetary Boundaries and the United Nations Sustainable Development Goals (SDGs), further enriches the discussion, providing a global context for the scientific principles taught in the classroom. These frameworks not only enhance the relevance of chemistry education but also inspire students with a sense of purpose and responsibility towards achieving a sustainable future.

Ethics, student agency, and future-oriented thinking are also explored in this volume, emphasizing the broader implications of chemistry education. By incorporating ethical considerations and fostering a sense of agency among students, educators can empower the next generation to take ownership in shaping a sustainable world. The concluding chapter offers a visionary outlook on what chemistry education might look like in 2050, challenging educators to think creatively about the future of their discipline.

More specifically, Chapter 1: The Sustainability Connection, introduces the fact that chemistry and sustainability are deeply intertwined. It explains how integrating sustainability into chemistry education can benefit students and their communities, setting the stage for the rest of the book. The chapter also offers practical tips for teaching sustainability-related topics, using the carbon cycle as an example. By framing sustainability as an integral part of chemistry, it encourages educators to rethink their teaching approach, ensuring that students are prepared to address real-world challenges.

Chapter 2: The Chemical Basis of Sustainability explores how chemistry, as the science of matter, is fundamental to understanding and addressing sustainability challenges. It introduces the concept of a systems-based perspective, which is crucial for understanding how human activities impact the planet. Teaching activities are presented to engage students with sustainability concepts, and a “chemistry for sustainability” pyramid is introduced. The chapter deepens the discussion by highlighting the role of chemistry in the material transformations that impact sustainability. It connects the abstract concept of sustainability with the tangible, scientific basis of chemistry, helping educators make these concepts more accessible to students.

The book then moves on to the evolution of sustainability in chemistry. Chapter 3, entitled *Orienting Chemistry Towards Sustainability*, describes how the concept of sustainability in chemistry has evolved from environmental chemistry to more recent concepts such as green, sustainable and circular chemistry. Through this chapter, the reader will understand the historical context and development of the field, while gaining an in-depth insight and broader perspective, showing how contemporary approaches to sustainability have emerged and why they are essential in today's world.

Chapters 4 and 5 aim to provide the reader with practical tools for more effective teaching. Entitled *Sustainability Tools I – Systems Thinking*, Chapter 4 discusses how systems thinking can enhance chemistry education by promoting meaningful learning and preparing students to address global sustainability challenges. It offers practical advice on how to integrate systems thinking into chemistry courses, encouraging gradual and sustainable

changes in teaching practices. This chapter is particularly useful as it provides educators with strategies to ensure that students develop the holistic thinking needed to address interconnected global challenges.

Similarly, Chapter 5: Sustainability Tools II – Impact-Based Metrics introduces these metrics as a way to evaluate the potential harm of chemicals, emphasizing the importance of considering the quality of chemical impacts rather than just their quantity. It also explains how life cycle assessment can be used to understand the environmental impact of chemicals. By focusing on impact-based metrics, this chapter highlights the importance of qualitative analysis in understanding environmental impacts, offering a practical tool for students to assess the sustainability of chemical processes.

This book offers two distinctive conceptual frameworks to introduce and make sense of sustainable chemistry: Planetary Boundaries (PB), a concept that describes the limits of the impact of human activities on the Earth system, and the United Nations Sustainable Development Goals, a shared blueprint for peace and prosperity for people and planet. In particular, Chapter 6: Sustainability Frameworks I – Planetary Boundaries introduces the concept of PBs, which provides a systematic approach to understanding Earth's complex systems and the role of chemistry in understanding and addressing them. It includes examples of how this framework can be integrated into chemistry education, particularly in relation to climate change. The chemistry educator will find this chapter particularly relevant as it links core chemistry concepts to Earth system processes, providing a structured approach to teaching sustainability in a global context.

On the other hand, Chapter 7: Sustainability Frameworks II – UNSDGs explores how chemistry can contribute to achieving the United Nations Sustainable Development Goals. It discusses how connecting molecular-level learning to socio-environmental problems can enhance systems thinking and provide context for sustainable practices in chemistry. By connecting chemistry education to the SDGs, this chapter broadens the scope of sustainability in the curriculum. It emphasizes the relevance of chemistry in solving global challenges, inspiring students with a sense of purpose and responsibility.

Personally, I found Chapter 8 particularly relevant and inspiring because it adds a moral dimension to the book and encourages educators to instill ethical awareness in their students, which is crucial for sustainable development. Chapter 8: Sustainability, Ethics, and Students successfully promotes the importance of including ethics in chemistry education. It argues that ethical considerations help students to think critically about the wider impact of chemistry and their responsibilities as future chemists.

Chapter 9: Student Agency in Sustainability is a good example of how chemistry education should put the learner at the center of the learning process. By focusing on student agency, this chapter emphasizes the active role that students can play in promoting sustainability. It provides educators with strategies to empower students and make them active participants in the pursuit of a sustainable future. I found particularly useful the case

studies that demonstrate how to promote awareness of the SDGs and engage students in proactive efforts to address sustainability challenges.

Finally, like any well-thought-out work, this book looks to the future and offers a glimpse of what chemistry education could, and perhaps should, be like in 25 years. Chapter 10: Imagining Chemistry Education in 2050 not only envisions how the subject might develop by 2050 but also encourages educators to think creatively about how they can continue to integrate sustainability into their teaching practices. This forward-looking chapter challenges educators to imagine the future of their discipline. It serves as a call to action, encouraging continued innovation in chemistry education to meet the evolving challenges of sustainability.

Leonardo da Vinci once said: “Learning never exhausts the mind.” As a professor, this truth has always resonated with me. However, my work with the International Union of Pure and Applied Chemistry (IUPAC) has deepened my appreciation and understanding of the importance of education in shaping a better and more just future for all. This conviction led me to co-edit the book *Chemistry Education: Best Practices, Opportunities and Trends*, driven by decades of research in chemistry education and the effectiveness of its findings in improving our teaching. Precisely because of that, I would like to take the opportunity of writing the foreword to this book to express my sincere gratitude to Mary Kirchhoff, Cathy Middlecamp, Klaus Kümmerer, and Peter Mahaffy for their invaluable contributions to *Chemistry Education for a Sustainable Future*. This timely and essential book addresses a critical issue and offers a rich array of perspectives and experiences. I wholeheartedly join them in their call to action for all chemistry educators to rethink and redesign our teaching methods to ensure that we not only impart knowledge but also make a meaningful contribution to the global effort to achieve a sustainable future. I am confident that this book will provide educators with the tools, strategies, and inspiration they need to make a lasting impact on their students and the world.

Prof. Javier García-Martínez, Chemistry Educator
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Preface

Chemistry plays a vital role in the emergence of sustainability, yet the connections among chemistry and sustainability are often overlooked in the chemistry curriculum. In an effort to close this gap, **Chemistry Education for a Sustainable Future** offers educators strategies and examples that connect chemistry education to sustainability. This approach aims to help students realize the central role that chemistry plays in achieving a sustainable world.

Throughout this book, we wish to meet the needs of educators who desire to do more with sustainability for *all* students but may not know how. Each chapter launches with “Opening Thoughts,” a brief rationale to set the stage. A section entitled “Background” then follows, offering readers more in-depth explanations of the concepts presented in the chapter together with useful references. By structuring their ideas in this way, the authors of each chapter first introduce readers to the sustainability-related content and then provide straightforward explanations.

The heart of each chapter is the third section, “Teaching and Learning a Sustainability Topic”. Here, our chapter authors offer practical suggestions to help readers reimagine how students in today’s classrooms and labs might learn chemistry. The teaching and learning sections provide concrete suggestions, activities, learning outcomes, and references to facilitate the integration of sustainability into the chemistry curriculum.

The foreword, written by Professor Javier García-Martínez, presents an excellent summary of each chapter. The content in these chapters builds to make the case that sustainability content can not only drive learning but can also benefit our students and the communities in which they live, preparing them for an interconnected and rapidly changing world. Ultimately, together with the professionals that our students will become, we can all practice chemistry to make the contributions to sustainability that are so urgently needed.

Finally, we wish to thank our outstanding chapter authors for composing such thoughtful, compelling narratives designed to lower the activation energy for you, our readers, to integrate sustainability into your chemistry courses. We are especially grateful to our colleagues at the Royal Society of Chemistry, Helen Armes and Amina Headley, for their prompt and detailed responses to our many questions and their guidance in editing this volume.

We hope you find this book useful in sharing your passion for and commitment to sustainability with your students.

Catherine Middlecamp
Mary Kirchhoff
Peter Mahaffy
Klaus Kümmerer

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Contents

Chapter 1	The Sustainability Connection	1
	<i>C. Middlecamp and M. M. Kirchhoff</i>	
1.1	Opening Thoughts	1
1.1.1	Consider the Needs of the Students Currently in Our Chemistry Classrooms	2
1.1.2	Consider the Needs of Communities	2
1.1.3	Consider the Needs of All Life on Our Planet	3
1.2	Background	6
1.2.1	Green Chemistry	7
1.2.2	Sustainable Chemistry	9
1.2.3	Systems Thinking	11
1.2.4	Circular Economy and Circular Chemistry	11
1.2.5	Artificial Intelligence (AI)	13
1.2.6	Tying it All Together	16
1.3	Teaching & Learning a Sustainability Topic	17
1.3.1	A Basic Understanding of the Carbon Cycle	17
1.3.2	Connections with Chemistry and the Chemistry Curriculum	19
1.3.3	Student Learning Outcomes	20
1.3.4	Activities, Pedagogies, and Real-world Examples	22
1.4	Closing Thoughts	24
	References	25

Advances in Chemistry Education Series No. 13
Chemistry Education for a Sustainable Future
Edited by Catherine H. Middlecamp, Mary M. Kirchhoff, Peter Mahaffy and Klaus Kümmerer
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Chapter 2	The Chemical Basis of Sustainability	28
	<i>S. Delaney and S. A. Matlin</i>	
2.1	Opening Thoughts	29
2.2	Background	29
2.2.1	Accelerating Changes to Planet Earth	29
2.2.2	Planet Earth as a Closed System (Mass)	30
2.2.3	Planet Earth as an Open System (Energy)	33
2.2.4	The Terawatt Challenge: Getting the Right Kind of Energy in the Right Place	33
2.2.5	The Biomass Factor	36
2.3	Teaching & Learning a Sustainability Topic	39
2.3.1	Earth's Material Resources (Example #1)	39
2.3.2	Material Circularity and Stewardship (Example #2)	48
2.4	Closing Thoughts – A Sustainability Framework for Chemistry	57
	References	59
Chapter 3	Orienting Chemistry Towards Sustainability	66
	<i>K. Kümmerer</i>	
3.1	Opening Thoughts	67
3.2	Background	67
3.2.1	Chemical Waste	68
3.2.2	Chemical Accidents	68
3.2.3	Environmental and Health Problems and the Rise of Environmental Chemistry	69
3.2.4	Pollution Prevention in Industry	71
3.2.5	Chemistry's Contribution to a More Circular Economy	71
3.2.6	Chemistry Within/For Sustainability	74
3.2.7	Interrelationships	76
3.3	Teaching & Learning a Sustainability Topic	78
3.3.1	A Basic Understanding of PFAS	78
3.3.2	PFAS Connections with the Chemistry Curriculum	83
3.3.3	Activities, Pedagogies, and Real-world Examples	87
3.4	Closing Thoughts	89
	Acknowledgements	89
	References	89

<i>Contents</i>	xv
Chapter 4 Sustainability Tools I – Systems Thinking	93
<i>M. Orgill, S. Donnelly and S. Delaney</i>	
4.1 Opening Thoughts	94
4.2 Background	94
4.2.1 Benefits and Challenges of Systems Thinking	95
4.2.2 Essential Characteristics of Systems Thinking	96
4.3 Teaching & Learning a Sustainability Topic – Ocean Acidification	99
4.3.1 An Overview of Ocean Acidification	99
4.3.2 Connections between Ocean Acidification and Foundational Chemistry Curricula	102
4.3.3 Using the ChEMIST Table to Iteratively Make Existing Lessons or Units More Systems Thinking Oriented	103
4.4 Teaching & Learning a Sustainability Topic – Lithium-ion Batteries	106
4.4.1 A Basic Understanding of Lithium-ion Batteries	108
4.4.2 A Basic Understanding of Lithium Sources, Lithium Processing, and Lithium Refining	110
4.4.3 A Basic Understanding of Lithium Recycling	112
4.4.4 Connections between Lithium-ion Battery Chemistry and Chemistry Curricula	113
4.4.5 Using Visualization to Represent Relationships Within and Across Systems and Identify Emergent Properties of a System	114
4.5 Closing Thoughts	128
Online Resources	129
References	130
Chapter 5 Sustainability Tools II – Impact-based Metrics	135
<i>A. Bongers and P. G. Jessop</i>	
5.1 Opening Thoughts	136
5.2 Background	136
5.2.1 What is Wrong with Mass-based Metrics?	136
5.2.2 An Introduction to Impact-based Metrics	138
5.2.3 Life Cycle Assessment	140

5.3	Teaching & Learning Impact-based Metrics	143
5.3.1	Student Learning Outcomes	144
5.3.2	First-year Chemistry and the First-year Undergraduate Curricula	145
5.3.3	Introductory Organic Chemistry: organicallychem.com	145
5.3.4	Upper-level or Specialized Undergraduate Curriculum	147
5.3.5	Activities and Practical Examples for Impact-based Metrics	147
5.4	Closing Thoughts	153
	References	155
Chapter 6	Sustainability Frameworks I – Planetary Boundaries	157
	<i>P. G. Mahaffy and S. E. Cornell</i>	
6.1	Opening Thoughts: Tracking Global Environmental Unsustainability Using the Planetary Boundaries Framework	158
6.1.1	Unsustainability is a Global Systems Challenge	158
6.1.2	The Planetary Boundaries Framework Shows How People are Changing the Planet	158
6.2	Background: Education for Global Environmental Sustainability	160
6.2.1	Structuring Chemistry Education for Sustainability Using the Planetary Boundaries Framework	163
6.3	Teaching and Learning Chemistry for Sustainable Earth and Societal Systems	165
6.3.1	Using the Planetary Boundaries Framework to Connect Chemistry and Sustainability	165
6.3.2	Teaching Chemistry and Climate Science with the Planetary Boundaries Framework	169
6.3.3	Activities and Resources to Connect Chemistry Concepts to Climate Change Through the Planetary Boundaries Framework	170
6.4	Closing Thoughts	181
	Acknowledgements	181
	References	182

<i>Contents</i>	xvii
Chapter 7 Sustainability Frameworks II – UN Sustainable Development Goals	184
<i>J. Wissinger</i>	
7.1 Opening Thoughts	185
7.1.1 Placing Chemistry in the Context of Sustainable Development	186
7.1.2 How Do the SDGs Help Prepare Students for Careers?	187
7.1.3 Education is Key to Achieving the Sustainable Development Goals	191
7.2 Background	192
7.2.1 Chemistry and the SDGs	192
7.2.2 Scaffolding the SDGs Across the Curriculum	192
7.2.3 Connecting Green Chemistry Principles, Systems Thinking, and the UN SDGs	194
7.2.4 Chemistry Societies and Web-based Resources	196
7.3 Teaching & Learning the UN Sustainable Development Goals	197
7.3.1 Polymers, Plastics, and the UN SDGs	197
7.3.2 Polymer Basics	197
7.3.3 Activity Set #1. The Benefits and Problems with Using Plastics	199
7.3.4 Activity Set #2. Designing More Sustainable Plastics for Meeting the SDGs	201
7.3.5 Activity Set #3. Single-use Packaging and the UN SDGs	203
7.4 Concluding Thoughts	209
References	211
Chapter 8 Sustainability, Ethics, and Students	215
<i>M. A. Fisher</i>	
8.1 Opening Thoughts	216
8.2 Background	217
8.2.1 Professional Ethics	217
8.2.2 Ways to Bring Professional Ethics into the Chemistry Curriculum	219
8.2.3 Resources for Connecting Chemistry to Ethics	223
8.3 Teaching and Learning a Chemistry Topic with an Explicit Ethical Dimension	224
8.3.1 Student Learning Outcomes	224

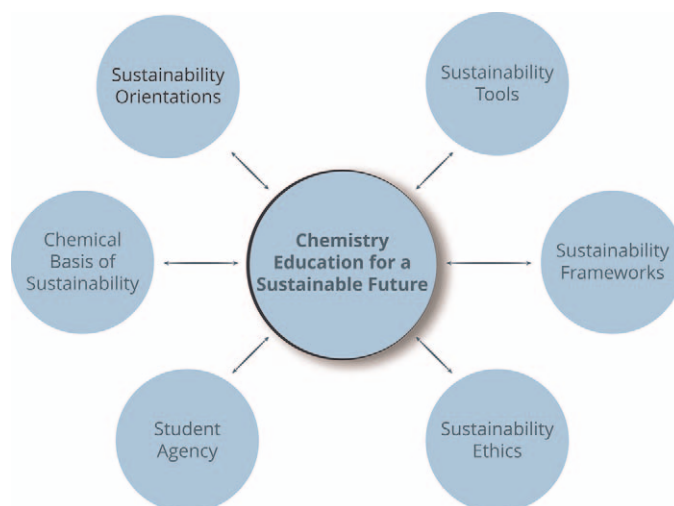
8.3.2	General Chemistry – Refrigerants, Lewis Structures, and Shapes of Molecules	225
8.3.3	Biochemistry – HIV/AIDS, HIV Protease, and Enzyme Catalysis	228
8.3.4	Assessment	229
8.4	Closing Thoughts	232
	References	232
Chapter 9	Student Agency in Sustainability	235
	<i>S. Rap, A. Sindiani-Bsoul, R. Mamlok-Naaman and R. Blonder</i>	
9.1	Opening Thoughts	236
9.2	Background	236
9.2.1	Education for Sustainable Development	236
9.2.2	Agency	237
9.2.3	A Framework for Student Agency in Sustainability	238
9.3	Two Case Studies	239
9.3.1	Methodology	239
9.3.2	Case Study #1: A Campus Sustainability Map	239
9.3.3	Case Study #2: “Speak to Me in Numbers”	243
9.3.4	Discussion	246
9.4	Closing Thoughts	248
	References	249
Chapter 10	Imagining Chemistry Education in 2050	251
	<i>M. Reynders and T. Holme</i>	
10.1	Envisioning the Future: Learning and Teaching in 25 Years	252
10.1.1	Questions About Learning	252
10.1.2	Questions About Teaching	254
10.2	Navigating Complexity: Visualizing the Teaching of Sustainability in Chemistry	256
10.2.1	Possible Subsystems	257
10.2.2	The Bigger Picture	261
10.3	The Role of Artificial Intelligence	264
10.4	The Role of Convergence	266
10.5	Influencing an Unpredictable Future	267
	References	269
	Subject Index	272

CHAPTER 1

The Sustainability Connection[†]

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1.1 Opening Thoughts

To support thriving human and ecological communities on Earth, chemists must adopt more sustainable practices. Chemistry and sustainability

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connect easily and well. As educators – urgently – we need to make these connections to ensure the viability of all life on our planet. At the same time, in a sustainable manner, we need to provide all people with the goods and services on which they depend. As chemistry educators, we play an important role in empowering the next generation; that is, those who will continue to work towards solutions for the challenges we face.

Tomorrow’s leaders are among the students in our classrooms today. How might we better position our students to become the next generation of leaders? This question is precisely the one that we will address in this book. More specifically, we have designed this book for those who want to integrate sustainability into their chemistry courses. Chapter by chapter, we make the case that connections to sustainability will benefit students, the communities in which they live, and ultimately all life on our planet.

1.1.1 Consider the Needs of the Students Currently in Our Chemistry Classrooms

These needs vary, depending on the chosen profession of the student. For example, some of our students will become chemists or chemical engineers. As future members of the workforce, they will need a broad range of skills, including current knowledge of safe, sustainable, and green practices. With this knowledge, they also can be more competitive in the marketplace, bringing up-to-date expertise both to their employers and to their fellow workers. Other students will become professionals in health-related or environmental fields; still others will earn degrees in education, agriculture, or law. For many such degrees, chemistry is a gateway course, one that students must complete to gain entry to a desired profession. What we should *not* offer to them is an outdated course, one crammed with material and possibly designed to weed out “the unfit”. Rather, by connecting the course to current challenges (*e.g.*, air, water, food, energy), we can both capture student interest and help our students to construct chemical knowledge that will be useful. Students should not leave our courses disgruntled, with any love of learning extinguished. All our students deserve instructors who can connect chemistry to the wider issues of sustainability, especially to those of human and planetary health. We urge instructors to devote special attention to foundational chemistry courses, because these may be the only ones our students will ever take.

1.1.2 Consider the Needs of Communities

Communities are the places from which our students come and to which they will return. All communities need energy, food, services, and products so that their members can lead healthy and productive lives. As a central science, chemistry at every level has something to offer communities. Its focus on atoms, molecules, and the related flow of energy provides a better understanding of where products come from, what they can be used for,

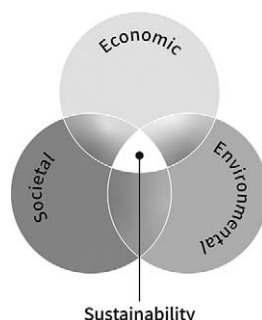


Figure 1.1 One of many ways to represent sustainability.

where they eventually end up, and which challenges accompany those products along their life cycles. Citizens who are broadly grounded, including in the sciences, are better positioned to wisely make use of resources and to make choices to benefit community members.

Communities face challenges that are multi-dimensional: economic, societal, and environmental. Not surprisingly, these same three dimensions comprise the Triple Bottom Line. Sustainable goods and services can be found at the intersection of the three circles (Figure 1.1). Today, some might argue to draw the circles of different sizes, while others make the case that the three circles should be drawn concentrically. Everyone, however, is likely to agree that paying attention to the interplay between economic, societal, and environmental factors is crucial in producing sustainable goods and services for a community and its members.

1.1.3 Consider the Needs of All Life on Our Planet

Chemical, physical, and biological indicators of the health of Earth system processes are changing rapidly. Because of the scale of human transformation of matter and energy, some geologists have recommended that we move the hands of the geologic time clock from the Holocene Epoch to a new proposed Anthropocene Epoch. Although this name change was voted down in 2024 by a committee of the International Union of Geological Sciences,¹ the dominance of the human imprint on planetary systems is unmistakable. Scientists recognize that the Holocene was a stable period in which average surface temperatures varied by less than one degree over 12 000 years, creating predictable climates that allowed humans and other creatures to thrive. Based on changes to geological markers in the Earth's crust, we may have transitioned in the 1950s to the proposed Anthropocene Epoch, reflecting humanity's impact on our planet.

1.1.3.1 Characterizing Sustainability

The concept of sustainability was first articulated in 1713 by Hans Carl von Carlowitz in his book *Sylvicultura Oeconomica oder Anweisung zur Wilden*

Baum Zucht (Sylvicultura Oeconomica or Instructions for Wild Tree Breeding). Von Carlowitz oversaw mining in Saxony, and wood was essential to the mining industry, providing timber for construction and fuel for smelting furnaces.² Von Carlowitz proposed implementing a science-based approach to forestry to ensure a sustainable supply of wood, advocating that wood should not be harvested at a rate that exceeded the rate of reforestation. In the context of sustainable forestry, von Carlowitz described the three pillars of sustainability: environmental, economic, and social justice, the same criteria depicted in Figure 1.1.

Today, sustainability is often described using the Brundtland Commission's definition of sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs".³ This definition does not address the sustainability of ecological communities and focuses less on preserving natural resources and more on society's ability to innovate its way to a sustainable future. Clearly, science and technology must play a central role in achieving this future. For example, the development of targeted fertilizers and pesticides is needed to increase crop yields to feed the more than eight billion inhabitants of our planet. Alternative energy sources are needed to enable the transition away from fossil fuels, and chemists are designing new materials to improve the efficiency of batteries for energy storage. Developing new products and processes must be done with the environment in mind, hence the need for chemistry that is green, sustainable, and circular.

The Planetary Boundaries framework, first published by an international interdisciplinary team led by scientists from the Stockholm Resilience Centre in 2009⁴ and with a substantial update in 2015,⁵ is a framework for understanding the safe limits of our planet. A 2023 visualization of the framework from the Stockholm Resilience Centre (Figure 1.2) enables us to quantitatively monitor the extent to which human activity influences individual Earth systems and the Earth system as a whole, how those influences interact dynamically with each other, and how they threaten sustainability. Tracking the rate of change to Earth system processes since this work was first published in 2009 shows striking changes over the intervening years in the risk to our planet from the scale and nature of human activity. To reflect those changes, as well as the dynamic interconnectivity of the Earth system processes that are represented, a new interactive learning tool for educators has been created⁶ and will be discussed further in Chapter 6.

As Chapter 6 will also describe, the chemical basis of sustainability is evident from looking at how changes to chemical parameters regulate many of the control variables for the nine biophysical Earth system processes in the framework. These Earth system processes in the Planetary Boundaries Framework and their control variables provide immediate and compelling contexts to introduce a wide range of chemistry concepts in foundational and other chemistry courses. Perspectives and assessment from the social sciences about the implications of these Earth system changes for environmental and intergenerational justice have also been integrated into this framework.

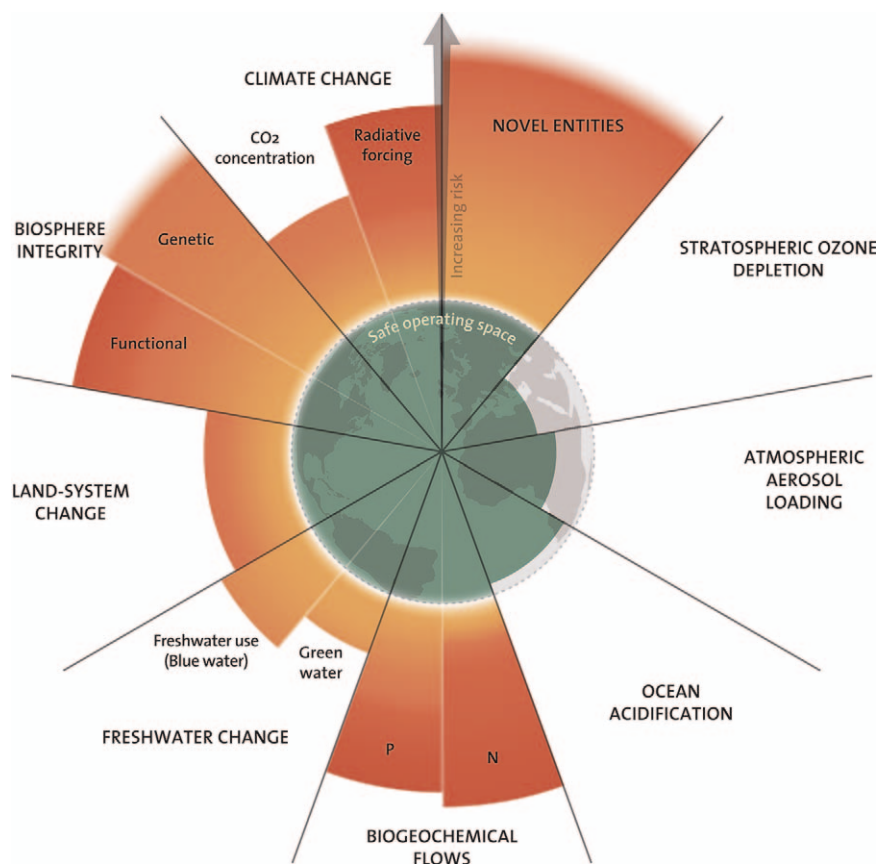


Figure 1.2 Planetary Boundaries concept that depicts the nine planetary boundaries within which humanity can continue to develop and thrive for generations to come. This figure from 2023 shows that six of these boundaries have crossed the safe operating space. Reproduced from <https://www.stockholmresilience.org/research/planetary-boundaries.html> with permission from Azote for Stockholm Resilience Centre, based on data from ref. 4 and 5.

The importance of chemistry in achieving sustainability is also evident in the 17 United Nations Sustainable Development Goals (UN SDGs)⁷ (Figure 1.3), which will be explored in more depth in Chapter 7.

Both the Planetary Boundaries and UN SDG frameworks can readily be mapped onto chemistry and other disciplines. Built into our characterization of sustainability is the responsibility to meet human needs and care for all creation, of which people are a part of a larger whole. All of humanity must steward our planet's life and resources, including the flow of matter and energy on which our modern society depends.

To bring these opening thoughts to a close, we offer both a disclaimer and a well-known question. First, the disclaimer. Rethinking a chemistry



Figure 1.3 The 17 United Nations Sustainable Development Goals. Reproduced from ref. 7 with permission from the United Nations. The content of this publication has not been approved by the United Nations and does not reflect the views of the United Nations or its officials or Member States.

curriculum to offer students sustainability-related content is no simple matter; instructors cannot simply “add sustainability and stir”. Matching our chemistry curriculum to the needs of our students, their communities, and our planet requires integration, diverse points of view, new contexts, and new tools, not simply adding content. Changes must incorporate systems thinking, which takes a holistic view of the role chemistry plays in Earth and societal systems.

The question that ends this section, perhaps asked by Albert Einstein (but certainly made by many others in recent years) is simply this: What is the definition of insanity? The answer: doing the same thing over and over again and expecting different results. We cannot expect chemists to practice more sustainable chemistry or citizens to make informed choices if we do not educate them differently. To do something differently, one needs additional resources. The next sections provide an initial set of resources, and the chapters that follow offer content examples and teaching pointers that are more in-depth.

1.2 Background

In this book, several interconnected approaches feature prominently, and a fundamental understanding of these approaches is essential to effectively integrate sustainability into the chemistry curriculum and to integrate chemistry into sustainability. Not all of these approaches that connect

chemistry to sustainability – green chemistry, sustainable chemistry, systems thinking, the circular economy, and circular chemistry – have a single agreed-upon definition. In this section, we describe the ways in which we will use these terms throughout the book.

1.2.1 Green Chemistry

Green chemistry is the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances.⁸ In the United States, green chemistry's roots stemmed from the Pollution Prevention Act of 1990;⁹ in Europe, Integrated Pollution Prevention and Control Council Directive 96/61/EC served as the impetus for green chemistry.¹⁰ Implementing green chemistry has historically been guided by 12 principles¹¹ (Box 1.1) that help shape a chemist's thinking in designing new, or modifying existing, chemical products and processes. These principles provide valuable guidance to chemists seeking to implement green chemistry but are not meant to limit the creativity of novel approaches beyond the 12 principles. Because it is difficult to identify a product or process that is truly green, "greener chemistry" would be a more accurate label as most new products or processes are greener compared to existing ones.

Since 1996, the U.S. Environmental Protection Agency has been recognizing academic researchers, small businesses, large companies, and government laboratories for their breakthroughs in green chemistry.¹² Many of these award-winning technologies have come from the pharmaceutical industry; for example, Merck & Co. received their 2019 Green Chemistry Challenge Award for redesigning the synthesis of the antibiotic Zerbaxa™.¹³ The new synthesis reduces raw material costs, increases yield, saves water, and reduces energy usage and the carbon footprint of the process. A key step in the revised synthesis replaced column chromatography with crystallization-based purification, thereby eliminating large volumes of solvent. Pharmaceutical examples of green chemistry are especially relevant to organic chemistry students, many of whom are pursuing careers in the health sciences.

Identifying if a new product or process is greener than what is currently on the market is challenging, and "greenwashing" is common when it comes to promoting green, greener, or "more sustainable" products to consumers. This is where metrics and other tools and approaches for comparative assessment come in. Companies that implement a new manufacturing process can quantify the differences with respect to greener, such as less toxic or lower volume of solvent used or volume of water saved, between the new and old processes. In the case of natural resources such as bioresources, sustainability issues may be more difficult to assess and quantify. Metrics such as E-factor¹⁴ can quantify the amount of waste produced per kilogram of product, though E-factor does not address the nature of the waste produced. Life Cycle Assessment (LCA) considers all energy and materials used as well

Box 1.1 Twelve Principles of Green Chemistry.

1. It is better to prevent waste than to treat or clean up waste after it is formed.
2. Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.
3. Wherever practicable, synthetic methodologies should be designed to use and generate substances that possess little or no toxicity to human health and the environment.
4. Chemical products should be designed to preserve efficacy of function while reducing toxicity.
5. The use of auxiliary substances (*e.g.*, solvents, separation agents, *etc.*) should be made unnecessary wherever possible and, innocuous when used.
6. Energy requirements should be recognized for their environmental and economic impacts and should be minimized. Synthetic methods should be conducted at ambient temperature and pressure.
7. A raw material or feedstock should be renewable rather than depleting wherever technically and economically practicable.
8. Unnecessary derivatization (blocking group, protection/deprotection, temporary modification of physical/chemical processes) should be avoided whenever possible.
9. Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.
10. Chemical products should be designed so that at the end of their function they do not persist in the environment and break down into innocuous degradation products.
11. Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.
12. Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.

From Green Chemistry: Theory and Practice, © Paul T. Anastas and John C. Warner, Oxford Publishing Limited. Reproduced from ref. 11 with permission from Oxford University Press, Copyright 1998.

as the impact of the energy and materials on health and the environment. However, conducting an LCA can be data intensive and time consuming, and the outcome depends on the systems boundaries set as well as the availability and quality of data used for it. Impact-based metrics will be examined in-depth in Chapter 5.

1.2.2 Sustainable Chemistry

Green chemistry and sustainable chemistry are often used interchangeably, but there are important distinctions between these terms, and different understandings of them. The Organisation for Economic Co-operation and Development (OECD) defines sustainable chemistry as “a scientific concept that seeks to improve the efficiency with which natural resources are used to meet human needs for chemical products and services. Sustainable chemistry encompasses the design, manufacture, and use of efficient, effective, safe, and more environmentally benign chemical products and processes”.¹⁵ Sustainable chemistry, which will be examined more fully in Chapter 3, can be described using a key set of characteristics, including systems thinking; sustainable and responsible innovation; ethics and transparency along the full life cycle of chemical products; alternative business models leading to the use of fewer chemicals; and sound chemicals management (Box 1.2).¹⁶

Box 1.2 Key Characteristics of Sustainable Chemistry.

1. **HOLISTIC:** Guiding the chemical science and the chemical sector towards contributing to sustainability in agreement with sustainability principles and general understanding and appreciating potential interdependencies including long-distance interactions and temporal gaps between the chemical and other sectors.
2. **PRECAUTIONARY:** Avoiding transfer of problems and costs into other domains, spheres and regions at the outset, preventing future legacies and taking care of the legacies of the past including linked responsibilities.
3. **SYSTEMS THINKING:** Securing its interdisciplinary, multi-disciplinary and transdisciplinary characteristics including a strong disciplinary basis but taking into account other fields to meet sustainability to its full extent. Application as for industrial practice including strategic and business planning, education, risk assessment and others including the social and economical spheres by all stakeholders.
4. **ETHICAL AND SOCIAL RESPONSIBILITY:** Adhering to value to all inhabitants of planet earth, the human rights, and welfare of all live, justice, the interest of vulnerable groups and promoting fair, inclusive, critical, and emancipatory approaches in all its fields including education, science, and technology.
5. **COLLABORATION AND TRANSPARENCY:** Fostering exchange, collaboration, and right to know of all stakeholders for improving the sustainability of business models, services, processes and products and linked decisions including ecological, social, and economic development on all levels. Avoiding all “green washing” and “sustainability washing” by full transparency in all scientific and business activities towards all stakeholders, and civil society.

6. **SUSTAINABLE AND RESPONSIBLE INNOVATION:** Transforming fully the chemical and allied industries from the molecular to the macroscopic levels of products, processes, functions, and services in a proactive perspective towards sustainability including continuous trustworthy, transparent, and traceable monitoring.
7. **SOUND CHEMICALS MANAGEMENT:** Supporting the sound management of chemicals and waste throughout their whole life cycle avoiding toxicity, persistency and bio-accumulation and other harm of chemical substances, materials, processes, products and services to humans and the environment.
8. **CIRCULARITY:** Accounting for the opportunities and limitations of a circular economy including reducing total substance flows, material flows, product flows, and connected energy flows at all spatial and temporal scales and dimensions especially with respect to volume and complexity.
9. **GREEN CHEMISTRY:** Meeting under sustainable chemistry applications as many as possible of the 12 principles of green chemistry with hazard reduction at its core when chemicals are needed to deliver a service or function whenever and wherever this complies with sustainability.
10. **LIFE CYCLE:** Application of the above-mentioned key characteristics for the whole lifecycle of products, processes, functions, and services on all levels, *e.g.*, from molecular to the macroscopic levels and all sectors in a pro-active perspective towards sustainability.

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This broader understanding serves as a guiding principle that strives to find a better solution to fulfil the service and function needed.

As can be seen from the two definitions, the intent of both green and sustainable chemistry is to design environmentally benign products and processes to produce the goods and services on which society depends while preserving the health of the planet. However, the scope differs in some respects. A greener synthesis designed in a research or academic laboratory may be an improvement over the current reaction scheme but will have minimal impact on sustainability if it never leaves the lab. If it leaves the lab, aspects beyond chemistry itself become important too, and the life cycle and ultimate fate of the products or substances produced is considered by sustainable chemistry. In other words, not every process and product that is greener is more sustainable. Improving the efficiency of using natural resources for chemical products and processes must also take into account the material and energy inputs needed to produce those natural resources, which leads us to the concept of systems thinking.

1.2.3 Systems Thinking

Systems thinking, which will be explored in Chapter 4, is “the ability to understand and interpret complex systems”, a straightforward definition offered by Evagorou and colleagues,¹⁷ and involves

- visualizing the interconnections and relationships between the parts in the system;
- examining behavior that changes over time; and
- examining how systems-level phenomena emerge from interactions between the system’s parts.

Systems thinking has long been integral to engineering and earth science education, is used in a more restricted sense in biology education, but only recently has become a focus of chemistry education.¹⁸ Systems thinking is complementary to the reductionist approach to learning that is common across science education.¹⁹ The reductionist approach is useful in transferring knowledge but falls short in engaging students to think holistically about the practice of chemistry. Holistic thinking, however, is critical to avoiding unintended consequences that can negatively impact sustainability.

Applying systems thinking to chemistry education may seem overwhelming but can be made accessible to students. One way to do this is to first view the system as a whole, then select (or create) a representation of the system to meet your educational needs. Finally, zoom in and have students explore the relevant parts of the system. For example, the carbon cycle is a system presented in the next section of this chapter. As shown in the student activities for the carbon cycle, adding or deleting carbon reservoirs changes the boundaries of the system (Figure 1.5b). Instructors can modify a representation of any system to focus on specific features relevant to the chemistry curriculum in the context of sustainability.

1.2.4 Circular Economy and Circular Chemistry

Chemistry plays a critical role in enabling the circular economy, in which materials, products, and services remain in circulation for as long as possible.²⁰ Currently, the economy operates under a linear model in which materials are extracted from the environment, manufactured into products, used, then discarded.²¹ This is often described as “take, make, dispose”. In a circular economy, the atoms and molecules making up those products are circulated, and at the end of the product’s life, repeatedly recycled within the economy. Shifting from a linear to a circular economy requires us to rethink the concept of waste, which should be viewed as a feedstock rather than as a product to be disposed of at the end of its useful life. This concept can be demonstrated in the teaching lab by using the product in one experiment as the starting material in another.

Keijer and colleagues²² proposed 12 principles for circular chemistry (Box 1.3), a parallel construct to the 12 principles of green chemistry. Some

Box 1.3 Twelve Principles of Circular Chemistry.

1. **Collect and use waste.** Waste is a valuable resource that should be transformed into marketable products.
2. **Maximize atom circulation.** Circular processes should aim to maximize the utility of all atoms in existing molecules.
3. **Optimize resource efficiency.** Resource conservation should be targeted, promoting reuse and preserving finite feedstocks.
4. **Strive for energy persistence.** Energy efficiency should be maximized.
5. **Enhance process efficiency.** Innovations should continuously improve in- and post-process reuse and recycling, preferably on-site.
6. **No out-of-plant toxicity.** Chemical processes should not release any toxic compounds into the environment.
7. **Target optimal design.** Design should be based on the highest end-of-life options, accounting for separation, purification, and degradation.
8. **Assess sustainability.** Environmental assessments (typified by the LCA) should become prevalent to identify inefficiencies in chemical processes.
9. **Apply ladder of circularity.** The end-of-life options for a product should strive for the highest possibilities on the ladder of circularity.
10. **Sell service, not product.** Producers should employ service-based business models such as chemical leasing, promoting efficiency over production rate.
11. **Reject lock-in.** Business and regulatory environment should be flexible to allow the implementation of innovations.
12. **Unify industry and provide coherent policy framework.** The industry and policy should be unified to create an optimal environment to enable circularity in chemical processes.

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of these principles mirror the green chemistry principles, while others are important to chemistry and its products within a circular economy, *e.g.*, the ladder of recycling. The circular chemistry principles are directed toward chemical industry for, as Keijer and colleagues note, “innovative chemistry designed with sustainability in mind is only effective when translated into economically viable applications”. Industrial chemistry, however, is seldom covered in the chemistry curriculum even though most chemists work in the industrial sector. Examples of circular chemistry can help bridge the gap between academic and industrial chemistry.

However, not everything that is more circular is more sustainable. In addition, it is important to understand that all these approaches are influenced by human values. In other words, nature does not know

“sustainability”, nor does it tell us what is greener, what we should circulate and recycle, or even what are more sustainable approaches and solutions. Humans must apply their expertise, as well as their values of environmental and intergenerational justice, to implement the solutions needed to ensure the sustainability of our planet.

Plastics often come to mind when considering material circularity since we are already familiar with recycling plastics. However, only 17 percent of all plastics are recycled globally and the rest winds up in landfills, the environment, or incinerated.²³ Plastics that make their way into the environment cause significant issues, especially for marine ecosystems, as demonstrated by the Great Pacific Garbage Patch. Applying systems thinking to the plastics problem demands that the full life cycle of plastics must be addressed from the start; in addition to considering whether feedstocks are made from renewable or non-renewable sources, plastics must be designed to be reusable, recyclable, or compostable.²⁴ In addition, we need to examine our current use of plastics and identify areas where we can eliminate the use of plastics, such as packaging, in the future.

1.2.5 Artificial Intelligence (AI)

Clearly, artificial intelligence (AI) has the potential to be a game changer, both for sustainability and for education. The answer to the question “Should we use AI?” appears to be a foregone conclusion. We already are using it, and so are our students. With these thoughts in mind, we offer this brief discussion of AI that addresses both how it has impacted sustainability and how instructors can use AI as they engage their chemistry students.

1.2.5.1 *Artificial Intelligence: Successes and Emerging Challenges*

Today, AI is already providing a technological boost to sustainable development. The World Economic Forum has identified four ways in which AI can accelerate sustainable development: (1) catalyzing innovation; (2) creating tools to identify climate risks and investment opportunities; (3) enhancing accountability and transparency through impact measurement and management; and (4) reshaping how society views sustainability.²⁵

Innovation is where chemistry excels. For example, the application of AI to drug discovery has shortened the time required to identify viable drug candidates from years to months. During the COVID-19 pandemic, Moderna combined AI algorithms with robotic automation to increase production of mRNAs (messenger ribonucleic acids) from 30 per month to around 1000 per month.²⁶ This enabled Moderna to produce an effective vaccine in less than a year from the start of the pandemic. The rapid development of COVID-19 vaccines highlights AI's impact in achieving Sustainable Development Goal #3, “Good Health and Well-Being”.

Artificial intelligence has both positive and negative impacts on SDG Goal #13, Climate Action. It can help reduce the impacts of greenhouse gas emissions by modeling climate change predictions, designing smart grids, and developing low-emission infrastructure.²⁷ However, the increased computing power required by AI is accompanied by large energy demands.²⁸ Today, much of this energy is produced by the combustion of fossil fuels, which in turn contributes to climate change, negatively impacting sustainable development.

1.2.5.2 *AI in Education: A Work in Progress*

Given that the field of artificial intelligence is changing rapidly, what words of wisdom might one offer to teachers and their students? It seems clear that:

- AI will continue to grow in its abilities.
- Some people fear the coming uses of AI; others welcome them.
- Students are already making use of AI; so are their instructors.
- At every level, people need policies regarding AI.

Let us consider the first two bullet points, as they are related. AI is still a work in progress, with new products with new abilities emerging at a rapid pace. Will computers take control someday, becoming smarter at everything than we humans are? At this point, nobody knows the answer to this question. In some regards computers already are smarter, faster, and perhaps even safer than humans. Think reading medical images. Think aircraft autopilots. Perhaps even think self-driving cars.

Regarding the third bullet point, we suggest obtaining AI usage data from where you live and work; that is, ask your students and colleagues if they currently are using AI. If so, how? In asking these two questions, expect the answer to the first to be “yes” and the answer to the second to contain a few surprises. For example, one student who responded “yes” told one of the authors that she used AI to generate a set of matrices to practice on before her upcoming linear algebra exam.

Finally, let us focus on policies, the last bullet point on the list. We suggest that all instructors place an AI policy statement in their syllabi, ideally prepared using input from students and colleagues. It is especially important for instructors to explain to students the rationale behind the AI policy in the context of the course goals.

Guidance in developing such policy statements is widely available online. One example from the University of Delaware Center for Teaching & Assessment of Learning identifies four approaches that could be considered in developing policies on the use of generative AI:²⁹

- Use prohibited.
- Use with prior permission.
- Use with acknowledgement.
- Use is freely permitted with no acknowledgement.

These approaches are starting points in developing AI policies for specific courses. Keep in mind that any course-level policy needs to harmonize with existing policies at the institutional level.

1.2.5.3 Using AI in Teaching Sustainability

One necessary skill in using AI is the ability to write and then successively refine prompts, the questions or commands that guide AI in generating content. Once practiced at writing and refining prompts, instructors can use AI to quickly generate useful text relating directly to sustainability. A second necessary skill is the ability to recognize hallucinations, which are responses that are meaningless, nonsensical, or incorrect.

As an example, consider these four prompts:

1. What are the 12 Principles of Green Chemistry?
2. Do any additional green chemistry principles exist?
3. How do the green chemistry principles connect with sustainability?
4. Rewrite the green chemistry principles for a first-year chemistry laboratory experiment on acids and bases.

The discussion that follows is based on the responses to these prompts, all produced using a generative AI chatbot.³⁰

For Prompt #1, the user's intention was merely to provide a starting point for a conversation with an AI chatbot. It is a question to which the answer is known (see Box 1.1). In this case, the correct answer was quickly generated.

Prompt #2 moves the conversation a step further by asking for more information. The AI response provided three additional green chemistry principles: Safer-by-Design, Life Cycle Assessment (LCA), and Circular Economy, also cautioning that these three were not as widely recognized as the first twelve. The AI chatbot also added a reminder that the field of green chemistry continues to evolve. However, to a reasonably expert user, this answer fell somewhat short. Safer-by-Design, LCA, and the Circular Economy are approaches, not principles. Missing from the AI response were 12 more green chemistry principles, proposed by Winterton,³¹ and the related green engineering principles.³²

Prompt #3 probes the ability of the chatbot to “think” about connections. In its response, the chatbot correctly responded that the green chemistry principles were “closely linked to sustainability”. The complete response is provided in Box 1.4.

Prompt #4 generated a helpful but lengthy response. Each green chemistry principle was rewritten for an acid-base experiment. For example, the first principle changed to “**Prevention:** Aim to minimize waste by carefully planning your experiment and using precise measurements”. These four examples demonstrate the power, as well as the limitations, of AI in teaching sustainability.

Box 1.4 An AI response to the prompt, “How do the Green Chemistry principles connect with sustainability?”

The **Green Chemistry principles** are closely linked to sustainability by promoting environmentally friendly practices in chemical research and industry. Let us explore this connection:

1. **Resource efficiency:** By minimizing waste and maximizing atom economy, green chemistry reduces resource consumption, contributing to overall sustainability.
2. **Safer chemicals:** Designing safer chemicals helps protect human health and ecosystems, aligning with sustainable development goals.
3. **Renewable feedstocks:** Using renewable raw materials reduces reliance on finite fossil resources.
4. **Energy efficiency:** Efficient chemical processes save energy, which is crucial for long-term sustainability.
5. **Circular economy:** Green chemistry encourages recycling and reuse, aligning with circular economy principles.

In summary, green chemistry fosters practices that harmonize with sustainable development objectives.

1.2.6 Tying it All Together

This ‘background’ section is designed to illustrate the connections among the key concepts that link chemistry and sustainability. Green, circular, and sustainable chemistry are orientations of our discipline toward the emergence of sustainability and are essential to staying within the planetary boundaries and achieving the UN Sustainable Development Goals. Practicing chemistry from a systems perspective enables chemists to view their art holistically. Green, circular, and sustainable chemistry are frameworks in achieving sustainability and are most effective when implemented from a systems-thinking mindset. Application of one of these approaches, such as applying green chemistry or circular chemistry principles to a chemical reaction or process, does not inevitably lead to the outcome of sustainability. Rather, sustainability is better thought of as emerging from the whole system, rather than considering the individual elements of that system.

In addition, this background section nodded toward an intellectual newcomer: Artificial intelligence. As one of the newer kids on the block, AI is growing up, truly a work in progress. Although not a framework like green, circular, or sustainable chemistry, AI nonetheless can play a role in sustainable solutions. However, in contrast to these frameworks, AI may be part of the problem, both today and in the years ahead.

The chapters in this book aim to introduce an integrated approach to teaching chemistry that enables students to see chemistry as a solution to,

rather than the cause of, environmental problems. Using the carbon cycle as an example, the next section offers practical guidance on teaching and learning a sustainability topic within the chemistry curriculum.

1.3 Teaching & Learning a Sustainability Topic

For instructors, we have good news: Many topics in sustainability are relevant to chemistry. Consider, for example, topics in agriculture, plastics, transportation, health, housing, and renewable energy that all are part of larger systems. These days, sustainability-related journal articles and news stories literally are “hot off the press”.

The not-so-good news? Although sustainability content may be readily available and even hot off the press, this content is unlikely to be in a form that instructors can use immediately. Instructors in classrooms, lecture halls, and laboratories need information in a useful form to engage their students. This book aims to meet this need, as each chapter will provide practical suggestions for teaching and learning a topic in sustainability that connects to chemistry.

Unlike the chapters that follow, this first chapter does not focus on a single topic; rather, it offers background information for several broad sustainability-related topics. Accordingly, the next section of this chapter offers practical suggestions for teaching and learning a broadly applicable topic: The Carbon Cycle. Readers can expect to find resources for teaching and learning other sustainability-related topics in future chapters.

1.3.1 A Basic Understanding of the Carbon Cycle

“The carbon cycle is nature’s way of recycling carbon atoms”.³³

For billions of years, carbon atoms have been on the move. These atoms (incorporated into chemical compounds) have journeyed along different pathways, some to reservoirs where their journeys slowed to a crawl; others to reservoirs where they continued to hop to different places on Earth. Indeed, nature reuses and recycles.

In recent decades, however, with the dramatic increase in scale of burning fossil fuels to produce heat, electricity, and to power transportation, humans have released an enormous number of carbon atoms into the atmosphere in the form of carbon dioxide molecules. Some of these CO₂ molecules have continued their journey to dissolve in the oceans, where they impact the health of marine ecosystems. Other CO₂ molecules, with their ability to trap heat, have remained in the atmosphere and changed the energy balance of the Earth system. The consequences of human activities continue to affect all life on Earth. Managing the flow of carbon atoms into the atmosphere and ocean continues to be one of the major sustainability challenges of the 21st century.

The carbon cycle shows the places where carbon atoms are found and the pathways along which these atoms move and are transformed into other

carbon-containing species. Many different representations of the carbon cycle exist, as an internet search will quickly reveal. Although these representations differ, they all illustrate that carbon is found in many different places on our planet, *i.e.*, “reservoirs”. These reservoirs include plants, animals, rocks, fossil carbon, oceans, fresh water, and, of course, the atmosphere.

The chemical form of carbon in each reservoir is likely to differ, for example, CaCO_3 in rocks, CO_2 in the atmosphere, hydrocarbons in petroleum, and many different forms in organisms. For each of these chemical forms of carbon, pathways exist that can move the carbon to other reservoirs. For example, the process of photosynthesis moves CO_2 from the atmosphere to carbohydrates in plants, which in turn may become food for animals and humans, which may lead to another transformation to CO_2 or organic biomass. As another example, the process of combustion can move the carbon found in coal, natural gas, petroleum, or wood to CO_2 in the atmosphere and then into the ocean.

However, the representations of the carbon cycle differ in the details. Some provide estimates of the size of the reservoirs, often in gigatonnes (= 1 billion metric tonnes) or teragrams (= 10^{12} grams, 1 million metric tons) of carbon. Some include a more detailed or inclusive set of reservoirs than others. Many include quantitative estimates of the flux or flow of carbon atoms among reservoirs. And some are more obviously “cyclic” and occur on different time scales than others. For example, the respiration and photosynthesis pathways clearly cycle carbon dioxide in and out of the atmosphere. In contrast, because the formation of coal, petroleum, and natural gas (fossil carbon) from living organisms takes millions of years, it is not as obvious that the carbon dioxide released by combustion can eventually cycle back to the fossil carbon reservoir.

No matter which representation is selected, all are simplifications. An example of a representation of the carbon cycle is shown in Figure 1.4.

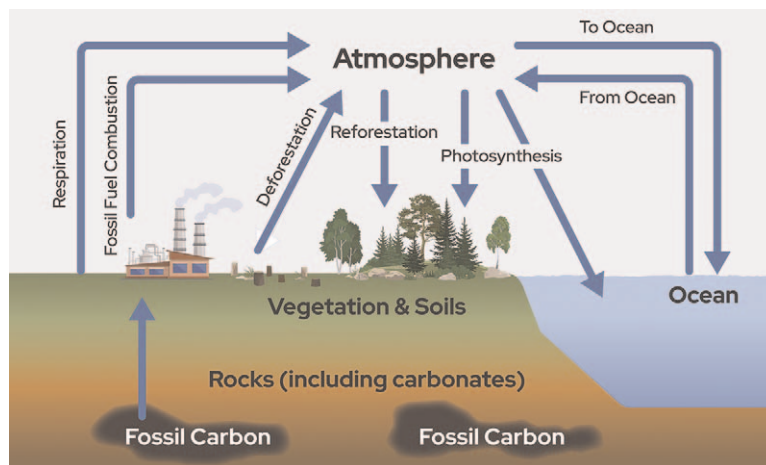


Figure 1.4 A representation of the carbon cycle, admittedly a simplification.

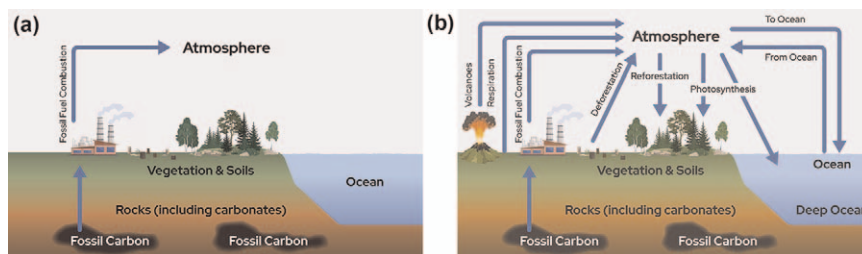


Figure 1.5 Two examples of modifications to the carbon cycle, both for instructional purposes. (a) Deletions of pathways to highlight fossil fuel combustion. (b) Addition of a volcano and a deep ocean reservoir to promote discussion.

As an instructor, you may wish to create your own representation of the carbon cycle. Doing so enables you to subsequently change this representation for different instructional purposes. A later section provides examples of how a carbon cycle representation can be altered by an instructor (Figure 1.5) in order to emphasize a point.

1.3.2 Connections with Chemistry and the Chemistry Curriculum

Let us first focus on the connections between the topic of climate change and the carbon cycle. Although climate change draws content from many disciplines, understanding it nonetheless requires chemical knowledge; in particular, knowledge of the carbon cycle.

Earlier, we pointed out that all carbon cycles show that (1) carbon compounds are found in many places on Earth, and (2) the carbon atoms in these compounds, over time, move at different speeds to different locations and sometimes to form different compounds. To understand how the carbon cycle connects to climate change, a third point is needed: (3) the place to which the carbon moves matters. More specifically, the carbon atoms that move from the fossil carbon reservoir to the atmospheric reservoir (primarily as carbon dioxide) are contributing substantially to global climate change. Box 1.5 lists these three points.

Climate change is but one item in a longer list of topics that connect the chemistry of the carbon cycle to sustainability. Ocean acidification is another, as the ocean is an enormous “sink” for carbon dioxide. Acid deposition on land is a third topic, not only because carbon dioxide makes rainwater slightly acidic but also because the oxides of sulfur and nitrogen are emitted when fossil fuels burn. Most of life, as we know it, is possible on our planet because of photosynthesis, which also connects to deforestation and food production.

Where is the home of the carbon cycle in the chemistry curriculum? Answer: at multiple points in the post-secondary chemistry curriculum,

Box 1.5 Practical suggestion #1.

Use these three points to launch a conversation with students about the carbon cycle:

1. Carbon (in different forms) is found many places on Earth.
2. It can move from one place to another.
3. Which place it ends up matters!

Table 1.1 A wealth of chemistry topics/issues connect to the carbon cycle. Many of these could be placed in more than one course.

Course	Chemistry topics
Foundational chemistry	Carbon compounds Names, chemical formulas Solubility of gases Ocean acidification, weak acids Chemical equations (combustion, carbonate reactions)
Organic chemistry	Hydrocarbons Petroleum as the source of organic feedstocks IR spectra of greenhouse gases Plastics and microplastics
Physical chemistry	Fuels, combustion
Biochemistry	Photosynthesis, respiration
Inorganic chemistry	Complex equilibria (carbonate, bicarbonate) Fossil fuels
Environmental chemistry	Atmospheric composition Carbon footprints Greenhouse gases Ocean acidification Carbon sequestration

including first-year chemistry, physical chemistry, organic chemistry, and biochemistry (Table 1.1). Consider, for example, the topics of photosynthesis and respiration. These two important chemical processes, often taught in an upper-level biochemistry course, also may have a home in a first-year course. Similarly, the combustion of carbon-based fuels fits easily and well in first-year topics such as chemical equations, stoichiometry, and thermochemistry. For courses with a geochemical focus, the formation and use of minerals and fossil fuels are relevant; hydrocarbons also play a prominent role in organic chemistry.

1.3.3 Student Learning Outcomes

Depending on the level of the course and the depth of the presentation, an instructor would write different sets of learning outcomes for the carbon cycle. Those listed first in Box 1.6 could be appropriate for foundational chemistry students or for students in an environmental chemistry course. Those listed next require higher level thinking skills and would be

Box 1.6 Sample learning outcomes for different chemistry courses.

Foundational Chemistry Courses

Given a representation of a carbon cycle, students should be able to:

- Identify the reservoirs and the carbon compounds in each reservoir.
- Identify the processes by which carbon atoms move between the reservoirs and the form (species) in which those carbon atoms are found.
- Write chemical equations for these processes, as appropriate.
- Explain a cause of global climate change.

More generally, students should be able to:

- List ways in which human activity has changed the carbon cycle, and summarize the consequences of these changes.
- Predict future pathways for carbon atoms in the carbon cycle.
- Create a diagram of a system that contains the carbon cycle.
- Propose a sustainability-related change in their community that connects to the carbon cycle and analyze its feasibility.
- Explain a cause of ocean acidification.

More Advanced Chemistry Courses

Students should be able to:

- Critique a representation of the carbon cycle, listing its strengths and weaknesses.
- Create a representation of the carbon cycle that shows estimates of the reservoir sizes.
- Create a representation of the carbon cycle that shows the relative magnitudes of “natural” and anthropogenic fluxes of carbon.
- Create two representations of the carbon cycle, one with a short time scale and the other with a longer one.
- Predict future pathways for carbon atoms in the carbon cycle.

Chemistry Courses with a Broader Scope

Students should be able to:

- List ways in which human activity has changed the carbon cycle, and summarize the consequences of these changes.
- Propose a sustainability-related change that connects to the carbon cycle, and analyze its feasibility.
- Propose a sustainability-related change in their community that connects to the carbon cycle and analyze its feasibility.

appropriate in more advanced courses. Finally, the last set of learning outcomes are broader in scope and may be useful to instructors at all levels who want to integrate sustainability into their courses and programs.

1.3.4 Activities, Pedagogies, and Real-world Examples

This section offers three sets of student activities (Box 1.7):

Activity Set #1 focuses on different representations of the carbon cycle.

Activity Set #2 offers practice in interpreting atmospheric carbon dioxide levels and assists students in understanding the units of concentration and the immense quantities involved.

Activity Set #3 contains open-ended questions related to fossil fuel combustion.

Box 1.7 Sample problems for Activity Sets #1, #2, and #3.

Activity Set #1

Decisions about the components of the carbon cycle

1. Should volcanoes be included in the carbon cycle? *Via* internet research, learn what mass of carbon dioxide they emit as compared to other pathways that produce carbon dioxide. Then argue for or against this statement: “Volcanoes emit far more CO₂ than humans do”.
2. Some carbon cycles show the deep ocean as a reservoir. Why? How does the deep ocean connect to carbonates and ocean acidification?
3. Look up data given in the latest Intergovernmental Panel on Climate Change (IPCC) report on warming from different greenhouse gases. Does this suggest that the flux of carbon atoms found in molecules other than CO₂ should be included in your carbon cycle?
4. Should plastics, possibly microplastics, be added as a reservoir in the carbon cycle? Currently, almost all carbon cycle representations omit plastics. On what basis would you argue for the inclusion or the exclusion of plastics? Recent data may prove useful.

Activity Set #2

Problems that connect to the levels of atmospheric carbon dioxide

1. What is a part per million? What is ppm a unit of? To what is it comparable? What is a gigaton (=a gigatonne)? To what is it comparable?
2. Look up a recent estimate for the concentration of CO₂ in the atmosphere in ppm. Cite your source(s).
 - a. Express this value in gigatons CO₂ and gigatons C.
 - b. How many years has it been since atmospheric CO₂ levels were this high?
3. Estimate the change in ppm CO₂ each year.
 - a. How many gigatons CO₂ and gigatons C is this?
 - b. What are the sources of this change?

4. Propose two of the most significant ways to “draw down” the concentration of carbon dioxide in the atmosphere. Comment on the feasibility of each one.

Activity Set #3**Problems (open-ended) that connect to fuel combustion.**

1. Estimate the amount of carbon dioxide released in burning a liter of gasoline/petrol.
2. Estimate the amount of gasoline/petrol burned in your city in one day.
3. Select three different fuels. Compare them based on energy released and carbon dioxide released when a kilogram of each fuel is burned. For each part, state your assumptions.

Box 1.8 Practical suggestion #2.

As the instructor, create your own representation of the carbon cycle, rather than using one from another source. Create each pathway separately so you can easily modify yours for use at multiple points in your course or in other courses in the curriculum.

The questions in each of these activities can be adapted for use in discussions, lectures, labs, or as a take-home activity, individually or in groups. Furthermore, student responses to these questions can serve as an assessment of what they know and are able to do. Predictably, some of the questions in these Activity Sets can be answered *via* an internet search or by generative AI, such as ChatGPT.³⁴ For example, a web search will provide answers to some of the questions in Set #2, offering an excellent opportunity for students to evaluate the quality of the information available on the web.

Here is a second practical suggestion for instructors who teach the carbon cycle (Box 1.8). Earlier, Figure 1.4 depicted a representation of the carbon cycle that was created using Microsoft PowerPoint. Here, we again point out that instructors who create their own representation of the carbon cycle can then make modifications that are useful for classroom activities. For example, an instructor might want to delete parts of the cycle in order to highlight a particular pathway or reservoir. Figure 1.5a shows this type of simplification, one easily produced from a home-generated graphic. Another possibility is to propose new reservoirs, such as the two shown in Figure 1.5b. Adding reservoirs gives students the opportunity to argue for or against the addition, reinforcing the idea that the boundary conditions of the carbon cycle are subject to interpretation and debate. As a third example, an instructor could question whether plastics should be included in the

carbon cycle. See Activity Set #1 (Box 1.7) for this and other questions about the merits of different representations of the carbon cycle.

1.4 Closing Thoughts

This chapter opened with the question of how we might better position our current students to become more engaged citizens and perhaps even the next generation of leaders. In part, we answered this question by highlighting the necessity of learning chemistry in ways that connect to sustainability, calling out the changes in our world that underlie this necessity. We also provided background material that describes the current understanding of sustainability, green chemistry, chemistry for a circular economy, sustainable chemistry, and systems thinking. A new curriculum is needed for both chemistry majors and nonmajors, so making the connections between sustainability and chemistry in first-year courses is critically important.

In the chapters that follow, we will address many of the issues that instructors face in teaching chemistry for a sustainable future. The graphic shown in Figure 1.6 serves to organize our approach.

The inner circle represents the goal – a transition to chemistry education for a sustainable future. The outer circles represent different parts that need to be integrated to achieve this transition. One outer circle will be

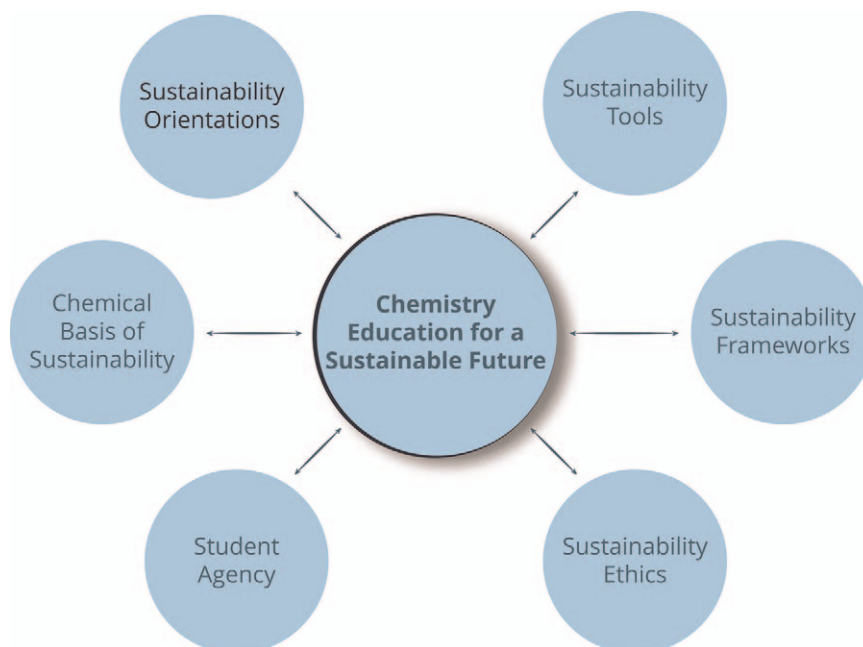


Figure 1.6 This graphic will be placed at the start of each chapter. One outer circle will be highlighted.

highlighted to indicate the content of the chapter. Finally, the double-headed arrows show that the connections are two-way, acting on each other in a system.

It could also be argued that the outer parts might better be represented with a hierarchy, all resting on chemistry as a material basis for sustainability.³⁵ Indeed, the next chapter focuses on this topic, addressing how understanding the molecular/material basis of sustainability provides a sound foundation for the chapters that follow.

Nonetheless, we have chosen to represent these parts in a circular fashion, all to be given weight in designing a chemistry curriculum. We suggest that these parts are interdependent, not to be approached in a linear fashion. This arrangement reflects the importance of systems thinking in considering all the parts. Although it might make sense for chemistry instructors to first examine the content of Chapter 2, readers can feel free to browse through the subsequent chapters in any order.

Again, this book is designed for those who want to integrate sustainability-related content into their chemistry courses. Chapter by chapter, this book will make the case that connections to sustainability can not only drive learning but can also benefit the learners and the communities in which they live, preparing them for an interconnected and rapidly changing world.

References

1. A. Witze, *Nature*, 2024, **627**, 249.
2. F. Schmithüsen, *Unasylva*, 2013, **240**(64), 3.
3. Sustainable Development Knowledge Platform, <https://sustainable-development.un.org/content/documents/5987our-common-future.pdf> (accessed August 2025).
4. J. Rockström, W. Steffen, K. Noone, Å. Persson, F. S. Chapin III, E. F. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, B. Nykvist, C. A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen and J. A. Foley, *Nature*, 2009, **461**, 472.
5. W. Steffen, K. Richardson, J. Rockström, S. E. Cornell, I. Fetzer, E. M. Bennett, R. Biggs, S. R. Carpenter, W. de Vries, C. A. de Wit, C. Folke, D. Gerten, J. Heinke, G. M. Mace, L. M. Persson, V. Ramanathan, B. Reyers and S. Sörlin, *Science*, 2015, **347**(6223), 736.
6. R. P. MacDonald, A. N. Pattison, S. E. Cornell, A. K. Elgersma, S. N. Greidanus, S. N. Visser, M. Hoffman and P. G. Mahaffy, *J. Chem. Educ.*, 2022, **99**(10), 3530.
7. United Nations, <https://www.un.org/sustainabledevelopment/> (accessed August 2025).
8. P. T. Anastas, L. G. Heine and T. C. Williamson, *Green Chemical Syntheses and Processes*, American Chemical Society, Washington, DC, 2000.

9. U.S. Environmental Protection Agency, <https://www.epa.gov/green-chemistry/basics-green-chemistry#definition> (accessed August 2025).
10. EUR-Lex Access to European law, <https://eur-lex.europa.eu/eli/dir/1996/61/oj/eng> (accessed August 2025).
11. P. T. Anastas and J. C. Warner, *Green Chemistry: Theory and Practice*, Oxford University Press, Oxford, 1998.
12. U.S. Environmental Protection Agency, <https://www.epa.gov/green-chemistry/green-chemistry-challenge-winners>, (accessed August 2025).
13. U.S. Environmental Protection Agency, <https://www.epa.gov/green-chemistry/green-chemistry-challenge-2019-greener-synthetic-pathways-award> (accessed August 2025).
14. R. A. Sheldon, *Chem. Ind.*, 1992, **23**, 903.
15. Organisation for Economic Co-operation and Development, <https://www.oecd.org/chemicalsafety/risk-management/sustainable-chemistry/> (accessed August 2025).
16. International Sustainable Chemistry Collaborative Centre, <https://isc3.org/page/sustainable-chemistry/key-characteristics-of-sustainable-chemistry> (accessed August 2025).
17. M. Evagorou, K. Korfiatis, C. Nicolaou and C. Constantinou, *Int. J. Sci. Educ.*, 2009, **31**(5), 655.
18. (a) See, for example, the December 2019 special issue on systems thinking of the Journal of Chemical Education, <https://pubs.acs.org/toc/jceda8/96/12> (accessed August 2025); (b) P. G. Mahaffy, A. Krief, H. Hopf, G. Mehta and S. A. Matlin, *Nat. Rev. Chem.*, 2018, **2**, 1.
19. M. Orgill, S. York and J. MacKellar, *J. Chem. Educ.*, 2019, **96**, 2720.
20. U.S. Environmental Protection Agency, <https://www.epa.gov/circular-economy/what-circular-economy> (accessed August 2025).
21. National Institute of Science and Technology, <https://www.nist.gov/circular-economy> (accessed August 2025).
22. T. Keijer, V. Bakker and J. C. Slootweg, *Nat. Chem.*, 2019, **11**, 190.
23. Ellen MacArthur Foundation, <https://ellenmacarthurfoundation.org/plastics-and-the-circular-economy-deep-dive> (accessed August 2025).
24. University of Minnesota Digital Conservancy, <https://hdl.handle.net/11299/211643> (accessed August 2025).
25. World Economic Forum, <https://www.weforum.org/agenda/2023/11/ai-sustainable-development/> (accessed August 2025).
26. A. Sharma, T. Virmani, V. Pathak, A. Sharma, K. Pathak, G. Kumar and D. Pathak, *BioMed Res. Int.*, 2022, **2022**, 7205241.
27. P. Dhar, *Nat. Mach. Intell.*, 2020, **2**, 423.
28. R. Vinuesa, H. Azizpour, I. Leite, M. Balaam, V. Dignum, S. Domisch, A. Felländer, S. D. Langhans, M. Tegmark and F. F. Nerini, *Nat. Commun.*, 2020, **11**, 233.
29. University of Delaware Center for Teaching & Assessment of Learning, <https://ctal.udel.edu/advanced-automated-tools/> (accessed August 2025).
30. Microsoft Copilot, <https://copilot.microsoft.com> (accessed August 2025).
31. N. Winterton, *Green Chem.*, 2001, **3**, G73.

32. (a) P. T. Anastas and J. B. Zimmerman, *Environ. Sci. Technol.*, 2003, **37**(5), 94A; (b) M. Abraham and N. Nguyen, *Env. Progress*, 2004, **22**, 233.
33. National Oceanic and Atmospheric Administration, <https://oceanservice.noaa.gov/facts/carbon-cycle.html> (accessed August 2025).
34. ChatGPT, <https://chat.openai.com> (accessed August 2025).
35. J. M. Whalen, S. A. Matlin, T. A. Holme, J. J. Stewart and P. G. Mahaffy, *ACS Sustainable Chem. Eng.*, 2022, **10**(39), 12933.

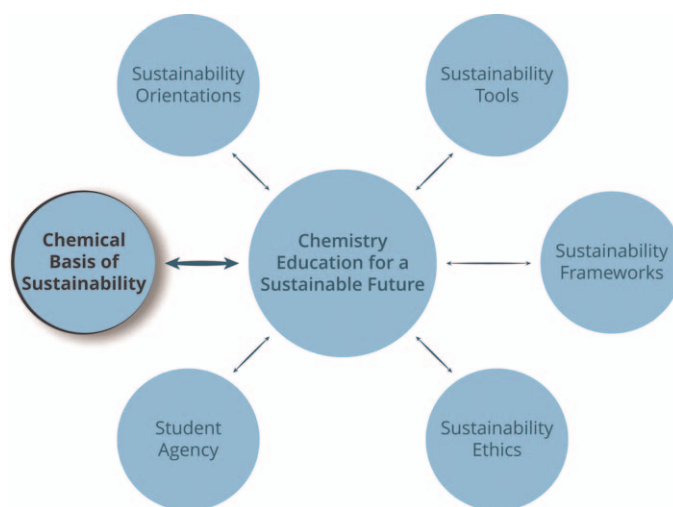
CHAPTER 2

The Chemical Basis of Sustainability[†]

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2.1 Opening Thoughts

This chapter considers how chemistry, as the science of the material basis of the world, has been fundamental to the transformations of matter through which people have exploited the Earth's resources. Sustainability connects how humankind is interacting with the world we live in with the ways this is affecting our planetary environment and with the long-term implications of these impacts for both people and the planet. Adopting this concept is a key imperative for chemistry, because the discipline is involved with understanding the structures and properties of matter and its processes of transformation and how materials interact with one another, including in biological and environmental settings.

Since human beings emerged on the Earth, they have become increasingly adept at transforming materials for their use. To survive, humans initially needed to grow and prepare food, make clothing and shelter, obtain heat and light, and provide security for individuals and communities. Over time, capabilities have been expanded to support work, well-being, travel, and leisure, including generating power, creating tools to help make material transformations more efficient and elaborate, developing machines for a host of applications, and manipulating biological processes to produce unique forms of biomass not readily found in nature. In order to consider the chemical basis of sustainability, this chapter will explore examples of these material transformations, as well as the energy required to put them into effect.

2.2 Background

This section examines the impact of human activity on the planet with respect to matter and energy. The Earth is largely a closed system with respect to matter and an open system with respect to energy. Chemistry will play a critical role in meeting the challenge of providing 60 Tw per day of power to the inhabitants of planet Earth by 2050. In addition, chemical innovations will be essential in utilising biomass as a source of chemicals and fuels.

2.2.1 Accelerating Changes to Planet Earth

The average wealth, life expectancy, and population of humans have changed over the last two millennia (Figure 2.1). The similarity of the three curves is striking. All show little change or only very slow growth until the last few hundred years. Starting in the 1800s, dramatic accelerations occurred that were enabled and built upon by successive agricultural, industrial, and digital revolutions. Advances in science and technology brought increasing use of mechanisation, automation, computerisation, and artificial intelligence tools to the processes of material transformation.

As a scientific discipline, chemistry played a substantial role in establishing the embodied material nature of the 21st century world in which we

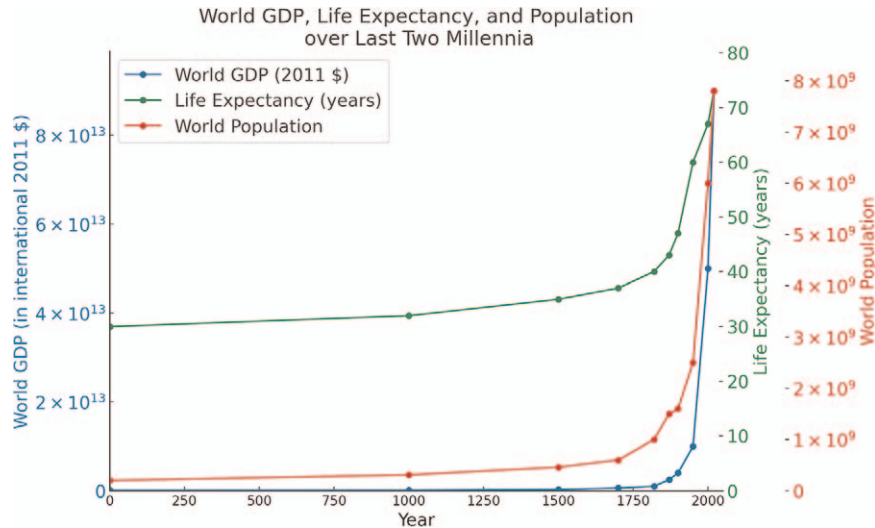


Figure 2.1 Wealth, life expectancy, and size of the Earth's population over the last 2 millennia. Data from Our World in Data, <https://ourworldindata.org/>.

now live. Chemists provided innovations and techniques relating to food production, preservation and nutrition, energy conversion, diagnosis and treatment of medical conditions, and manufacture of goods for commercial exploitation.¹

However, this period also saw corresponding changes in the planetary environment. The structure and functioning of Earth systems have been impacted by other great accelerations that are linked to shifts in the distribution of materials in our lands, waters, and atmosphere, especially from around the mid-20th century.²

To date, increasing productivity and meeting the growing demands from an expanding global population for food and material goods have only been possible by an increasing acceleration in how we transform matter. Figure 2.2 charts the rate at which 'anthropogenic mass' (the mass embedded in inanimate solid objects made by human beings) has increased since 1900 and compares this with the amount of the dry weight of living biomass on Earth.³ Box 2.1 provides questions that an educator could use to promote a more holistic classroom discussion around the implications of an ever-increasing production of anthropogenic mass.

2.2.2 Planet Earth as a Closed System (Mass)

To a first approximation, a fixed amount of matter is present on Earth (close to 6.0×10^{24} kg), *i.e.*, Earth is a 'closed' system. In fact, some new matter arrives at the Earth's surface every day in the form of about 25 million micrometeorites and meteorites. Overall, about 5.2×10^6 kg of cosmic dust per year settles to the Earth's surface.⁴ This dust is composed of elements such

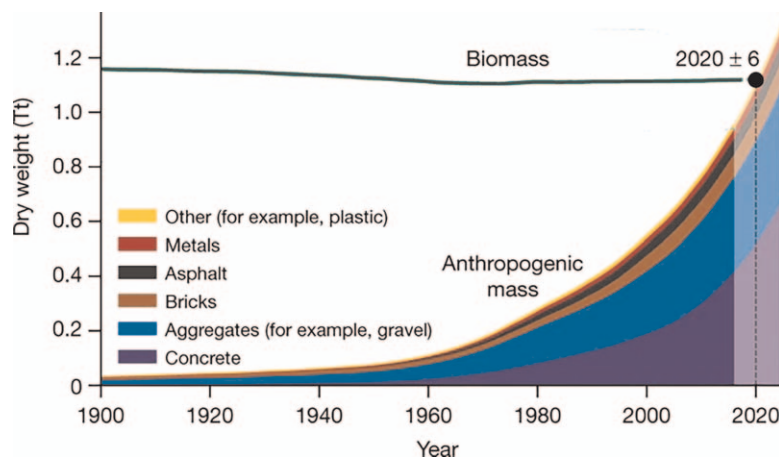


Figure 2.2 Changes in the Earth's anthropogenic mass and biomass (dry weight) since 1900. Reproduced from ref. 3 with permission from Springer Nature, Copyright 2020.

Box 2.1 Discussion questions – patterns in anthropogenic mass and biomass.

Figure 2.2 and other related studies modelling the production of anthropogenic mass³ on regional, national, and global scales align with chemistry's contribution to recent shifts in human activities. These questions could launch student inquiries into chemistry's central role in establishing the modern material-built environment in which we live.

- Global biomass has been relatively constant but slightly decreasing for more than a century.
 - What could be contributing to this slight decrease?
 - Anthropogenic mass has doubled every 20 years since 1900. By 2020, it had reached 30 Gt per year and the amount in active use totalled about 1.1 trillion tonnes present on the planet. Which human activities are most important in driving this expansion in material transformation? Explain your reasoning.
- The same study³ reported that the amount of global mass-produced plastic (~8 Gt) is now double the overall mass of all terrestrial and marine animals combined (~4 Gt). This evidence has been used to support claims that we have entered a new geologic Epoch, the 'Anthropocene'.
 - What evidence suggests that this transition from one epoch to another is directly related to chemistry's contribution to material transformation?

as carbon, oxygen, iron, and other atoms heavier than hydrogen and helium.⁵ At the same time, the Earth's atmosphere, which has a mass of about 5×10^{18} kg, is leaky and loses about 9×10^3 kg of gases daily into space. This mass is primarily hydrogen and helium, as well as oxygen, which becomes ionised by solar energy in the upper atmosphere, acquiring enough velocity to escape.^{6,7} The total gas loss amounts to around 75×10^6 kg per year. The net outcome is that the Earth's mass is very slowly shrinking, but on a timescale that will take billions of years to be significant.⁸

Accumulating evidence of the linkages between the increasing exploitation of the Earth's inanimate and biological resources and the impact this is having on our planet's physical and biological systems has caused mounting concern. For millennia, we have acted as if the planet were an infinite resource and sink, capable of providing as much material as we might want and of tolerating as much waste as we might produce.⁹ Questioning this approach, in the 1960s the idea of 'Spaceship Earth' began to attract attention, with the Earth being likened to a space vessel on a long journey and having a fixed quantity of materials that would need to last for the entire voyage.

We travel together, passengers on a little space ship, dependent on its vulnerable reserves of air and soil; all committed for our safety to its security and peace; preserved from annihilation only by the care, the work, and, I will say, the love we give our fragile craft.

Adlai Stevenson, speech to the United Nations, 1965¹⁰

The 1966 book, *Spaceship Earth* by economist Barbara Ward, an early advocate of 'sustainable development', pioneered thinking on the overlap between the environment and development, making connections between wealth distribution and the conservation of planetary resources.¹¹ The economist Kenneth Boulding also used the spaceship analogy in the title of his 1966 essay, *The Economics of the Coming Spaceship Earth*.¹² Contrasting with the past open economy model of apparently limitless resources, Boulding wrote, "The closed economy of the future might similarly be called the 'spaceman economy', in which the Earth has become a single spaceship, without unlimited reservoirs of anything, either for extraction or for pollution, and in which, therefore, man must find his place in a cyclical ecological system". Thus, it would be necessary to minimise, rather than maximise, consumption. In 1969, architect and designer-inventor Richard Buckminster Fuller published an *Operating Manual for Spaceship Earth* in which he noted that Spaceship Earth had departed without the people aboard receiving operating instructions for the vessel.¹³ The occupants were having to discover or invent them on the journey and had to work together in order to keep the planet functioning properly.

In 1972, the Club of Rome published *The Limits to Growth*,¹⁴ also referred to as the Meadows Report. The report gained worldwide attention and is often cited as influencing today's degrowth movement.¹⁵ The book expressed the view that the Earth's interlocking natural resources would not be

able to continue supporting the present rates of economic and population growth indefinitely and that five basic factors would ultimately limit growth: population increase, agricultural production, non-renewable resource depletion, industrial output, and pollution generation.

2.2.3 Planet Earth as an Open System (Energy)

As discussed in the previous section, to a first approximation the Earth behaves like a closed system with respect to matter, having a fixed amount of a material present (at least, on a human timescale). By contrast, with regard to energy, the Earth is an 'open' system, because solar radiation constantly bathes the planet and some is absorbed.

Why is the potential for increasing use of solar energy so important? The amount of solar radiation potentially available for our use is massive. The average intensity of solar energy reaching the top of the atmosphere directly facing the Sun is about 1360 watts per square metre. In one hour, the Earth receives a total of 173 000 Tw of energy from the Sun, which is about 10 000 times the amount of energy that we currently use (*e.g.*, in 2017 humanity used 160 000 Tw of energy in the whole year).¹⁶

While energy cannot be created or destroyed (First Law of Thermodynamics), it can be converted from one form into another. It appears that a combination of methods of energy conversion, including wind, wave, geothermal, hydroelectric, solar, and nuclear, could potentially meet the world's energy demands in the coming decades while also satisfying the 'net zero' goal for greenhouse gases.

2.2.4 The Terawatt Challenge: Getting the Right Kind of Energy in the Right Place

The growing array and scale of human activities creates ever-increasing demands for energy as well as matter. Human beings have learned to convert energy from a variety of sources, especially burning organic materials (from fossil carbon and biomass). Humans have also harnessed the power from 'renewable' sources such as wind, water, solar, and geothermal forms and by capturing the energy released during nuclear reactions. However, with the combustion of carbon compounds being the predominant source of energy, the levels of carbon dioxide (CO₂) in the atmosphere have been rising, resulting in climate change. The countries of the world have collectively committed to a goal of 'net zero' – reducing net emissions of CO₂ and other greenhouse gases into the atmosphere to as close to zero as possible by 2050, with any remaining emissions to be re-absorbed from the atmosphere.¹⁷

Early in the 21st century, chemistry Nobel laureate Richard Smalley coined the term 'the Terawatt Challenge'.¹⁸ In 2004, Smalley observed that the world had used, on average, 14.5 Tw per day of power (1 terawatt (Tw) = 10¹² watts) – equivalent to burning 220 million barrels of oil per day. He estimated that,

beyond the need to replace combustion-generated power with a comparable level from sources that did not emit CO₂, total power production would have to increase fourfold to about 60 Tw per day by 2050 to accommodate the rising global population and increasing demand from under-served regions. Smalley pointed in particular to solar, wind, and geothermal power generation – especially the first of these – as having the greatest potential for providing the majority of the world’s power in 2050. However, he emphasised that getting there would be extremely difficult and that new technologies will be needed.

Where does chemistry come into the picture? Chemistry is central to at least four critical areas of meeting the Terawatt Challenge in ways that are sustainable:

1. **Capturing energy:** whichever approach is adopted, physical materials need to interact with the energy source and convert the energy into a useful form of power. Methods that rely on movement, such as the flow of wind, waves, and water from rivers or dams, use turbines, and these machines must be set in rigid encasements of concrete and steel and contain windings of conductive wire and powerful magnets to convert motion into electric current. Geothermal power generation, capturing heat from deep underground, requires pipes and equipment involved in the circulation of fluids and transfer of the heat to other fluids and/or conversion into electric current by using heat and pressure to drive turbines. Methods to trap energy from the sun may use solar panels fitted with arrays of photocells (Figure 2.3a) that convert electromagnetic radiation into electric current or convert the trapped energy into heat in a water reservoir. For some of the stages, sophisticated materials are required to make the processes effective and efficient – for example, wind turbines (Figure 2.3b) are fitted with powerful permanent magnets made from rare-earth metals like neodymium,

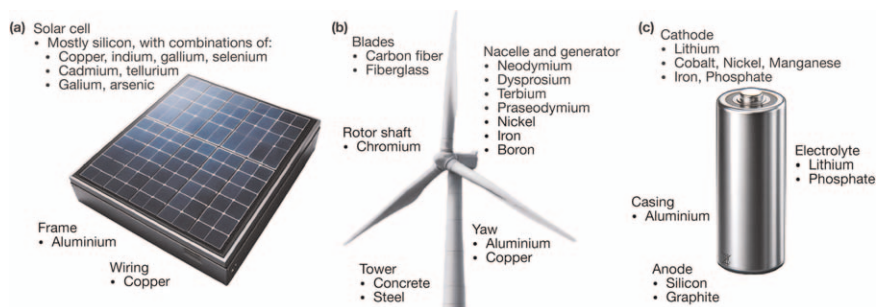


Figure 2.3 Examples of structures and materials in energy devices. Figure drawn by Delaney, incorporating images created using ChatGPT; (a) photovoltaic array for trapping sunlight; (b) wind turbine; (c) lithium-ion battery.

praseodymium, dysprosium and terbium, whose supplies are limited and whose mining has had a history of environmental damage.¹⁹ Photocell devices use combinations of conductors, semiconductors, and resistors.²⁰

2. **Transporting/transmitting energy:** unless the energy is captured or derived from fuel at the precise site where it is used, it needs to be transported or transmitted over distances that may span a range from local to global. The main options at present are to physically move fuels such as coal, oil, gas, biomass, or waste to sites where they will be combusted, or to transmit electricity from the site of production *via* conducting materials. In practice, the two are often combined, with fuels being transported to power stations and the electric power generated transmitted through large power grids to the users. Both transport and transmission are intensively matter-dependent, requiring vehicles, fuels, structures of concrete and steel, and conductor cables and their insulations.
3. **Storing energy:** an advantage of deriving energy from combustion is that it can be carried anywhere and used at any time. Many of the 'renewable' sources of energy (*e.g.*, wind, wave, solar) fluctuate over time and cannot be relied upon to produce a constant or predictable power supply on demand. Therefore, it is essential to have the means to store energy, which can be accumulated when instantaneous supplies are in excess of demand and made available when these supplies fall short. Infrastructures for energy storage, which may be chemical or physical in nature,²¹ require materials, for example in the construction of batteries (Figure 2.3c), reservoirs, heat exchange systems, and the structures that house them.
4. **Providing mobile energy:** systems that require energy to be available while on the move present particular challenges. For vehicles (*e.g.*, cars, ships, aircraft), combustible carbon-based fuels have been the main motive force. Alternatives under development to help meet the 'net zero' goal include batteries for land-based vehicles and the use of non-carbon fuels (*e.g.*, hydrogen and ammonia) for land- and ocean-based vehicles. Aviation (which accounts for 2–3% of global CO₂ emissions) is proving the greatest challenge, with the main focus of attention being on 'renewable' or 'sustainable' sources of hydrocarbon fuels derived from biological sources. For other mobile applications, including portable information technology equipment such as computers and smartphones, rechargeable batteries are used. Although each individual battery may be small, the aggregate on a global scale is massive, with about 7 billion smartphones in circulation worldwide in 2024.²² Currently, most rechargeable batteries (including for vehicles and phones) are based on lithium-ion technology (Figure 2.3c), employing compounds of lithium and cobalt, with available supplies of these 'critical' elements being a major factor in the potential for expanding battery production.

Although the total energy availability on Earth is in principle ‘open’, the conversion globally from fossil fuel to renewable energy sources is dependent on the ‘closed’ availability of matter present on the planet. All the hardware infrastructure necessary to capture/convert and supply energy in different forms, when and where needed, depends on ingenuity to find and transform the matter into appropriate materials. The innovativeness of chemists, material scientists, engineers, and others is essential in making this possible.

2.2.5 The Biomass Factor

Biological processes transform nutrients containing carbon, hydrogen, nitrogen, oxygen, phosphorus, and traces of many other elements into the molecular constituents of life. Human beings have acquired great skill in adapting life forms to supply needs for food, clothing, shelter, and construction materials, and in processing and transforming biological materials to make many specialised products we find useful, from paper to pharmaceuticals. The renewability of biological resources offers a pathway to solve some of the sustainability challenges we currently face. It is vital, however, to understand both the potential and the limits of biological avenues, just as it is for chemical ones. Also of importance is to appreciate that biological and chemical approaches share many common features and co-determinants. At a molecular level, biological processes are fundamentally chemical processes, and chemistry provides an entry point for understanding how they take place.

The biosystems of our planet provide several different but interdependent functions. These include serving as the planet’s “lungs” (absorbing CO₂ and emitting O₂), as sources of materials for human use, and creating chains and webs of nutrients that interlink all life-forms on the planet. There are finite spaces where different life-forms can flourish on the planet, and the growing impact of human activity on these spaces has been a major factor in growing environmental crises, such as the competition for available freshwater supplies. Water availability will increasingly become an issue, particularly in arid regions, as even a small decrease in freshwater availability may represent a ‘tipping point’ signifying detrimental impacts on human and non-human health.

These factors are vital to consider when the potential of biology is being evaluated to solve sustainability challenges. For example, in principle, developing biofuels to replace fossil fuels appears useful. Biofuels come in various forms and types; bioethanol has been successfully produced and marketed from corn (a primary source for American biofuel), sugarcane (especially in Brazil), and soybean (primary sources include Brazil and other Latin American countries). The viability of bioethanol has been seen as an economic issue, as the growth and processing of the crop represents a majority of the cost,²³ so bioethanol production has been most profitable in countries where agricultural costs are low. The industry also uses a

substantial percentage of arable land and water that would otherwise be used to grow a diverse range of food sources. Often this requires cutting down forests to develop the land for biomass production, or substituting production of edible crops, which can have negative impacts on climate change, biodiversity, and food and water security. These last two are sometimes referred to as the ‘food *versus* fuel’ and ‘water *versus* fuel’ debates.

As an example of how the factors intersect, North Africa and Australia are potential areas for massive solar energy generation with global significance.^{24,25} These areas could be used to power large-scale electrolysis of water to produce hydrogen and ammonia to ship overseas, for instance to Asia and the EU.²⁶ However, North Africa suffers from drastic water shortages and unreliable access to electricity. Considering the relative priorities and trade-offs involved in achieving security of energy, food, and water supplies in different settings provides many opportunities for classrooms of students to debate such ‘food *versus* fuel’ and ‘water *versus* fuel’ issues and their linkages to chemistry and systems thinking (Box 2.2). For the students, there should not be a clear ‘winner’ of the debate; rather, it should demonstrate how competing parties can manipulate interpretation of the science for their own interests, and how science–society relationships have contributed to increasing inequality through an accelerating global demand for energy, food, and water.

Ultimately, the use of biomass as a source of organic compounds for synthesis is an important avenue to escaping dependence on diminishing fossil hydrocarbon reserves. This is a challenge for synthetic chemistry which, since the mid-19th century, has become habituated to using hydrocarbon feedstocks and seeking ways to increase functional groups through selective oxidation reactions. A switch to biomass sources means learning to selectively reduce oxidised compounds like carbohydrates to make the chemicals needed for all kinds of applications.

The biomass and energy sectors are also interlinked in another major way; namely, the reliance on hydrogen gas sourced from fossil fuels to produce ammonium-based fertilisers, without which the world could not produce enough food to feed its global population. So-called ‘green hydrogen’, which is produced from the electrolysis of water *via* a renewable energy source, has been proposed as an alternative. A renewable source of hydrogen also provides pathways to metal and steel production that require a significantly smaller amount of fossil fuels.²⁵ Hydrogen, in molecular form or carried as ammonia, could be used as a fuel for transportation or be sent abroad for use as a fossil-fuel alternative. The argument then could be made that this provides a means to ‘export’ renewable energy (coining the phrase “shipping sunshine”²⁷) to countries where it is less economic or practical to produce renewable energy.

However, the amount of water needed to produce green hydrogen (and green ammonia) on a scale that could displace fossil fuels as a hydrogen feedstock is astronomically large.²⁸ Access to fresh water will compete with

Box 2.2 'Food *versus* fuel' and 'water *versus* fuel' as classroom debates.

As an activity, the 'food *versus* fuel' and 'water *versus* fuel' debates involve students undertaking a stakeholder analysis of an important chemistry-focussed socio-scientific issue. Students should inquire and reflect upon competing perspectives: the grower; the fuel provider; the transport industry; the government; climate advocates; and the community.

This can be an individual task, but the most benefit comes from running the activity with small groups of students that are asked to take different sides on the socio-scientific issue and have a classroom debate.

A good prior activity would be to compare a range of fossil fuels and biofuels as energy sources, and carbohydrates, proteins, and lipids as fuel sources for the body. Students should be able to write balanced thermochemical equations for the combustion of various fuels.

These questions could stimulate a 'food *versus* fuel' or a 'water *versus* fuel' debate:

- Arable land used for energy production (biofuel) is land not used for food production. What is more important, food security or energy security? Does this vary for different countries? How does this work when food chains are global, and energy companies are multinational?
- An alternative is to use waste biomass, or agricultural biomass that is not marketable or viable to feed a population. But can an industry relying on a waste bioproduct ever be big enough to provide a viable transition away from fossil fuels? Should large amounts of arable land ever be used to grow a crop that *can't* be a food?
- Another alternative would be to use a source of plant biomass that does *not* take up arable land. For example, different types of seaweed or macroalgae could be cultivated in a warehouse, a lake, or offshore. However, is this swapping one problem for another, with oceans and aquatic environments already impacted by climate change and biodiversity loss?
- Parts of the chemical and energy sectors want to utilise so-called 'green hydrogen' to decouple from fossil fuels. But this involves gaining access to already limited fresh water supplies and may entail consumption of scarce local water supplies to generate fuel for export. Is this equitable? Will energy from the massive solar energy farms and fresh, desalinated water be prioritised for the local community, or for industry? Ultimately, for whose benefit would be the green hydrogen?

food production, as well as with other public needs (see Box 2.2). Seawater could be used, but it would first need to be desalinated on a large scale, producing a waste material (concentrated brine) that will either need to

be stored or returned to the ocean, impacting aquatic ecosystems. Therefore, if electrochemical green hydrogen²⁶ production is to be viable, it will need to demonstrate that it will not diminish the availability of biomass and water.

2.3 Teaching & Learning a Sustainability Topic

A significant feature of the emerging understanding of sustainability has been that it provides a systems-based perspective. Understanding how systems operate – including how system components interact and how overall properties of the system emerge as a result of the working of the whole system – turns out to be crucial to identifying the ways that humanity's activities impact sustainability at the planetary level. Consequently, chemists, as well as environmental scientists, need to acquire some facility for systems thinking (see Chapter 4).²⁹

Analysis of systems often begins with examining the stocks and flows of the system components and resources in order to look at how they interact and what intended or unintended consequences follow. In light of the growing demands of an increasing global population wanting more food and goods, we need to focus our attention on two sets of resources, materials and energy, and ask:

- What are our current sources of materials and energy, how do we use them, and what impacts have their utilisation had on Earth systems?
- Can we continue to expand the supplies of materials and energy to sustain current rates of growth? What do we know about the limits to availability of these resources on our planet?
- What are the possible alternatives to ever-increasing the supplies of them?

This section presents two activities focused on our current materials resources. The first, a student infographic on an element, is an example of how students can engage with the sustainable and ethical utilisation of a material (Section 2.3.1). The second, a student essay on material stewardship, is an example of how students can more deeply explore the sustainability of a material of their choice (Section 2.3.2). Each activity is preceded by background information for the instructor, possible connections to the chemistry curriculum, and possible learning outcomes.

2.3.1 Earth's Material Resources (Example #1)

2.3.1.1 A Basic Understanding of the Earth's Material Resources

The periodic table of the elements provides chemists with a catalogue of all the known elements, listed in increasing atomic number and organised into

rows and columns according to similarities and trends in their properties. To chemists, it represents a fundamental means to organise the elements and helps explain what type of bonding forms between elements. Elements are categorised relative to the number of protons in the nucleus, and so the table also provides the scientific community certainty that it represents all matter that exists.

The periodic table shown in Figure 2.4 colours each element according to its abundance in the Earth's crust, with the most abundant (>10 000 ppm) in green, intermediate abundancies in yellow, and the least abundant (<100 ppm) in pink.³⁰ The white squares (and a few of the pink ones, like radon and uranium) represent elements that have radioactive isotopes. Some are formed naturally by the radioactive decay of heavier radioactive elements (*e.g.*, radon from uranium) or have been created experimentally in tiny amounts by nuclear reactions.

Figure 2.4 outlines some important lessons concerning sustainability: (1) a finite number of elements exist on Earth, (2) of these elements, only about 80 have at least one stable isotope and are therefore safe for routine use; and (3) the majority of the elements, including many of value in making useful materials, are available only at relatively low abundances. Consequently, we need to carefully conserve the available stocks of elemental resources and keep them in usable forms for as long as possible, rather than

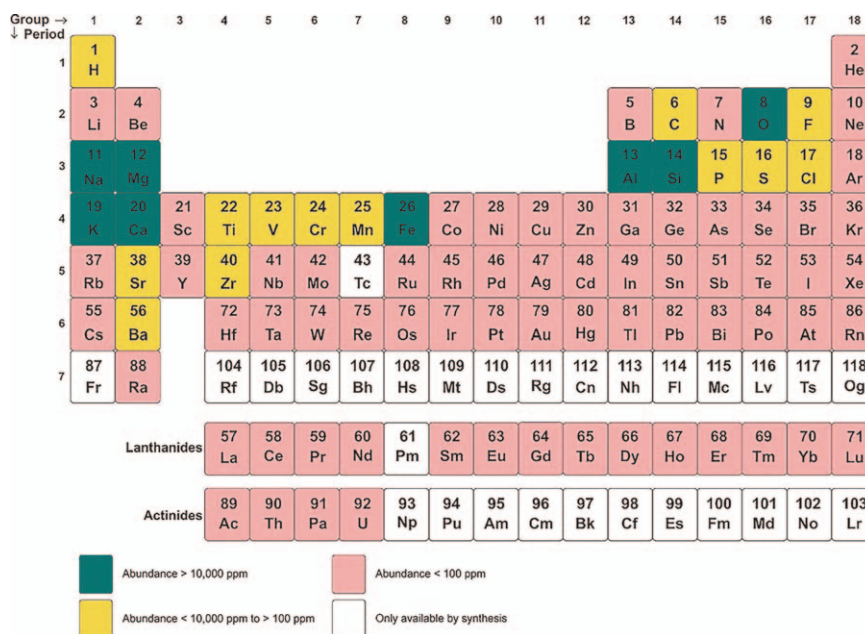


Figure 2.4 Periodic table of the elements: natural abundances in the Earth's crust. Reproduced from ref. 30 with permission from John Wiley & Sons, Copyright © 2019 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.

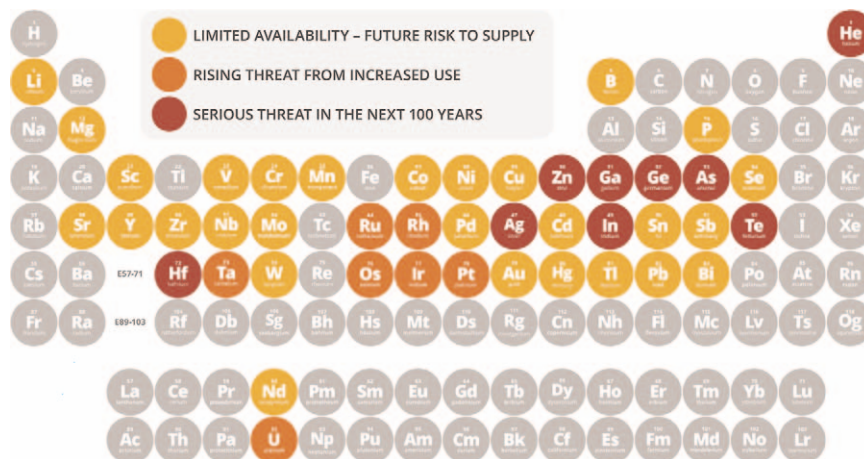


Figure 2.5 Periodic table of the endangered elements: Relative threat to availability. Reproduced from ref. 31 with permission from American Chemical Society.

disperse them in ways that make recovery technically or economically impractical.

In addition to differing in their overall abundances, elements also differ in their distribution across the planet. For example, some elements are concentrated in just a few locations in amounts that make them economical to extract and use them at large scale. There has been increasing awareness and concern about the limited supplies of some elements that have specialised and important uses, which have been termed ‘gateway minerals’ and ‘critical’ and ‘endangered’ elements.^{31,32} Figure 2.5 represents the elements of the periodic table relative to how endangered each element is, reflecting how seriously nations and global organisations should consider the threat that these elements will not be so easily available to future manufacturing sectors.

Some countries have adopted policies recognising the high strategic importance of some of these materials for their physical and economic security, including their use in sourcing renewable energy, battery powered vehicles, and battery storage.^{33–36} Since 2011, the European Commission has listed raw materials that it considers to be critical elements or compounds according to both their strategic importance for future technology and their scarcity. This list, updated every three years, has grown rapidly: it contained 14 entries in 2011, 20 in 2014, 27 in 2017, 30 in 2020, and 34 in 2023.³⁷ In 2021, the Australian federal government’s leading science body, Commonwealth Scientific and Industrial Research Organisation (CSIRO), published a critical energy minerals ‘roadmap’,³⁶ and in 2023, on top of a list of critical minerals similar to EU, USA and India lists, published a separate shorter list of “strategic minerals”.³⁸ These minerals, namely aluminium, copper, nickel, phosphorus, tin, and zinc, were singled out as important to the global

transition to a clean and renewable energy sector, abundant and accessible in Australia, and importantly in demand from Australia's strategic international partners.³⁸

Following the discovery of mineral deposits, the mining, transport, and processing of ores consumes additional materials, including fuels to transport and chemicals to process. In addition, all of the equipment (mining equipment, haulage transport, industrial plant infrastructure) must be built and maintained, which requires materials and energy. At every step along the pathway to finished goods, from the mining site onwards, there are also waste products to be dealt with, that can be harmful to the environment.

In 2017, world mining production³⁹ was 17.2 Gt (1 gigatonne = 10^9 tonnes), double the production level in the early 1980s and with quantities dominated by ores of iron (93% of all ore mined globally), aluminium, copper, lead, and zinc. However, the International Energy Agency reports that in order for a clean energy future to be realised, nonfuel mineral mining globally will need to massively increase, with over forty times the amount of lithium (albeit from a small amount, only 130 000 tonnes were extracted in 2021)⁴⁰ and twenty times the amount of cobalt and nickel needed.⁴¹ Collectively, these amounts are still dwarfed by the amount of oil extracted each year,⁴² so in a potential clean energy future, *less* minerals will need to be extracted from the Earth. However, much of this nonfuel mining extraction will occur not in the handful of oil-rich nations but in countries not known previously for mining, which will itself bring social implications for governments and socio-political challenges for the global society (explored further in Chapter 4).

2.3.1.2 Connections to the Chemistry Curriculum

When students start to learn about the periodic table, they also learn about early efforts to categorise, classify, and order the elements. The most famous of these 'scientific discovery' narratives is that of Dmitri Mendeleev, who took advantage of accumulating evidence collected during the middle parts of the 19th century on the properties of pure elements. Mendeleev discerned that there was *periodicity* in the properties of elements that suggested a repeating cycle (periods) for elements that had similar properties but very different atomic masses (groups). Mendeleev's enduring legacy is related to his gumption to extend this conclusion to (correctly) leave gaps in his table for elements not yet discovered and even predict (almost correctly) the properties of these unknown elements, such as *eka-aluminium* (gallium).

2.3.1.3 Learning Outcomes

Curricula worldwide now challenge students to replicate the thought experiment of Mendeleev, and typical learning outcomes related to this are listed in Box 2.3.

Box 2.3 Learning outcomes – relating properties and characteristics of elements to their position in the periodic table.

Given an element's position in the table, students should be able to:

- Predict its relative chemical reactivity (with the bottom left corner being the most reactive metal, and top right (bar the noble gases) being the most reactive non-metal).
- Predict other properties based on periodic trends, such as atomic radius, ionisation energy, and electronegativity.
- Predict an electron configuration for the element and its number of valence electrons, linking this configuration to the chemical properties of the element (such as noble gases are inert, alkali metals are highly reactive) and to the type of ion or ions (in the case of transition elements) that this element can typically be found as in nature.
- Write an empirical formula when reacted with other elements, such as the formation of metal oxides, metal carbonates, metal chlorides, and so on.

The opposite would also be true: given some of these properties or characteristics, a student would be expected to determine its relative position in the periodic table.

Box 2.4 Learning outcomes – relating sustainability considerations of elements to their position in the periodic table.

Given an element's position in the table, students could investigate:

- The electrical energy requirements of processing an element that does not exist as a pure element in nature.
- The relative difficulty of separating and purifying an element when it is found in combination with other elements, either due to:
 - how close these different elements are to each other on the periodic table, with nearby elements (same period, same group) routinely having similar chemical and physical properties; and
 - the relative abundance of one element compared to other elements in a given mixture, be it a solid or solution.

To give a more sustainability-relevant focus, students could also consider real-world scenarios and utilisation of these trends. The learning outcomes (Box 2.4) offer some possibilities.

Sourcing an element found in miniscule amounts poses significant economic and environmental considerations for industry. The difficulty of separating and purifying elements with very similar chemical and physical properties makes it difficult and uneconomical, for instance, to recycle all electronic waste. It also makes it challenging to separate and purify lithium

from its most abundant source, the oceans, where ions with similar properties such as sodium are in far greater abundance.

2.3.1.4 Activity: An Infographic on an Endangered Element

Popular in secondary/high school settings is to have an ‘element poster’ assignment as part of the chemical/physical science teaching and learning sequence. In such activities, students are tasked to make a poster, presentation slide, or infographic about their chosen element, with instructions guiding them to include information about the element. Typical assessment criteria for this kind of assignment are listed in Box 2.5.

The ‘element poster’ activity was popular during the International Year of the Periodic Table celebrations (2019), with the International Union of Pure and Applied Chemistry (IUPAC) and other organisations running or supporting student competitions collecting artistic representations of the elements and the periodic table.⁴³ However, much of the list is reductionist, isolating knowledge about the element to a series of easily verifiable facts. As presented, this activity does not challenge students to critically reflect on *why* the element is considered important and if its current utilisation is sustainable.

This activity would be more challenging if some items from this list were added or replaced with questions that were more holistic and required critical reflection about how the *chemistry* of the element has led to a

Box 2.5 Typical assessment criteria for an ‘Element Poster’ task.

Students could be assessed on their capacity to include items such as:

- The element’s name, symbol, atomic number, and mass number.
- The element’s classification as a metal, a non-metal, or a metalloid.
- The element’s state at room temperature and its melting and boiling points.
- The element’s location on the periodic table period and group.
- The electron shell configuration (*e.g.*, Na: 2, 8, 1), shown as a Bohr shell model.
- The sub-shell configuration (*e.g.*, Na: $1s^22s^22p^63s^1$ or $[\text{Ne}]3s^1$), and perhaps the orbital filling pattern and electron spin (up and down arrows).
- The relative abundance of common isotopes.
- Common uses for the element, or common household items/built environment where the element may be found, perhaps with a photo showing the element in use.
- Relevant safety information if the element has high reactivity or is considered hazardous.

An artistic drawing from the student that symbolises the element.

significant over-utilisation of the element, and/or has become limited in supply. Box 2.6 presents a set of such questions to include in an activity asking students to prepare an infographic on an 'endangered element'.

Figures 2.6 and 2.7 present example infographics for zinc and tantalum, respectively. Both elements are essential to our modern material world, zinc for protecting the built environment from corrosion, and tantalum for capacitors in most electronic devices. Both elements have been added to critical element lists globally,³⁶ and both of their supply chains are considered under stress, but for different reasons. Zinc is one of the top ten mined elements in the world,^{44,45} yet is predicted to be one of the first elements in short supply and is already reliant on mining very-low-quality ore.⁴⁶ An obvious solution would be to rapidly increase the recycling rate of a metal that is relatively easy to recycle.

In contrast, only approximately 2000 metric tons of tantalum are mined each year.⁴⁴ It is almost exclusively mined in a few countries, with more than

Box 2.6 Assignment – 'Endangered Elements' infographic/advertising campaign.

Students are to prepare and/or present an endangered element infographic/advertising campaign. To influence the target audience (*e.g.*, government representatives, industry organisations, or members of the public), this infographic should address some or all of these questions:

- Why is the element considered essential for modern society?
- How has the element become 'endangered'?
- Where and how is this element sourced, and does this raise concerns regarding the sustainability of the element as a resource?
- What can we do in response to the 'endangered' status?

In supporting students, instructors should consider:

1. Any of the endangered elements identified in Figure 2.5 would be a suitable choice. Students may be more interested in elements used in electronic devices (see Section 2.3.2.1.3 – smartphones) or in electric vehicles.
2. Given it is an infographic and poster campaign, students should be encouraged to make them **emotional** and **visual**, with as few words as possible. As an advertising campaign, the intention here is to raise awareness of an issue that has the potential to negatively impact our livelihoods (for instance the need to improve recycling of e-waste). When answering the prompting questions above, students should be encouraged to incorporate **social**, **ethical**, **economic**, and **environmental** factors.
3. Several free online infographic generator tools are available, including those that allow students working remotely or online either individually or collaboratively to prepare their infographic.



Figure 2.6 Example endangered elements infographic for the element zinc.⁴⁴⁻⁴⁶
 Figure drawn by Delaney, incorporating images created using ChatGPT.

half coming from countries destabilised by previous or current armed conflicts. One such country is Rwanda, which supplies approximately 22% of the global supply, but it is speculated that significant amounts of this supply are illegally smuggled in from neighbouring war-torn Democratic Republic of Congo,⁴⁷ which already supplies over 40%. This raises significant ethical concerns regarding how tantalum is sourced, which can be used in an advertising campaign to stimulate people to question if their desire for the



Figure 2.7 Example endangered elements infographic for the element tantalum.⁴⁷
Figure drawn by Delaney, incorporating images created using ChatGPT.

latest model phone is exacerbating the hardship faced by people in these countries (Figure 2.7).

A possible extension to this activity would be to have students include connections to specified United Nations Sustainable Development Goals (SDGs) (see Chapter 7), to link the criticality of the element and the urgent need for action with addressing sustainable development challenges. Assessment criteria that could be incorporated into a rubric are listed in Box 2.7.

Box 2.7 Typical assessment criteria for an ‘Endangered Elements’ infographic/advertising campaign task.

Students could be assessed on their capacity to include items such as:

- Outlining how and why the element is considered essential for modern society, and how this has led to the element being considered ‘endangered’.
- Linking how the element is *sourced* to one or more important social, ethical, economic, or environmental factors.
- Linking how the element is *utilised* to one or more important social, ethical, economic, or environmental factors.
- Providing the audience, a lay person, or a chemistry expert, an example of an action they can take to improve or not further exacerbate the element’s ‘endangered’ status.
- Using visuals and emotive language in their infographic that could influence the opinion of either a lay person or a chemistry expert.
- Describing at least one example of how industry or academic research is focussing on more sustainable production, utilisation, or recycling of the endangered element.

2.3.2 Material Circularity and Stewardship (Example #2)

2.3.2.1 A Basic Understanding of Material Circularity and Stewardship

Circularity is an important concept in trying to find a pathway to a sustainable future. For most of humanity’s history, the economic model underlying consumption has been a ‘linear’ one of take-make-use-dispose. This model was epitomised in the 1950s when the ‘throwaway society’ was encouraged, as disposable goods became increasingly cheap and easily replaceable. Subsequently, reaction against this wastefulness of materials led to the ‘reduce, reuse, recycle’ (3Rs) campaign and the idea of the ‘circular’ economy, in which materials are collected at the end of their primary use and refurbished, repurposed, or broken down and components returned as manufacturing inputs. In the circular model, only as a last resort are materials discarded as waste and consigned to landfills or incineration.

In principle, material circularity deals with at least two factors important for sustainability:

- Preserving material components for reuse helps extend the availability of valuable matter and lengthen the period before we use up the accessible planetary stocks.
- Cutting down the amount of waste material to be disposed of lessens the environmental burden. According to World Bank estimates,⁴⁸ global generation of municipal solid waste alone exceeded 2 billion tonnes per

year by 2018 and is predicted to rise by 70% by 2050. The growing amount of solid waste encroaches on more land, and its decomposition produces toxic liquids that may leach into the surrounding soil and water and emissions of gases, including CO₂ and CH₄, that add to the global greenhouse effect. Furthermore, the discharge of liquid and gaseous wastes from household, industrial, or agricultural sources into the atmosphere and waterways is often uncontrolled and unmeasured.

However, material circularity does not automatically produce sustainability. Knowing that a given material is recycled in some form does not tell you whether the material was sourced and produced sustainably in the first place, or what new materials and energy inputs are required for the specific recycling approach chosen, or how side-products and wastes that are inevitably created at every stage along the recycling pathway are dealt with.

In a typical chemistry reaction system, reactants combine to afford the desired product under conditions that depend on many factors, including solvents, catalysts, temperature, pressure, and conditions of mixing. When a process is run at large scale, concern for sustainability requires that we ask about the supply and disposal systems, accounting for the material and energy inputs and outputs. For the products then taken up in useful applications, we also need to consider the materials and energy involved in the applications, where they come from, and what disposal systems are employed at the end of the primary application. All of these considerations help build a comprehensive picture of the overall production, consumption, and disposal system.

Consideration of sustainability requires that we also ask about how this production, consumption, and disposal system impacts Earth systems associated with land, atmospheric, and aquatic systems. These physical systems interact with one another and with the biological and ecological systems of the planet. As the Planetary Boundaries Framework tells us (see Chapter 6), there are limits to how much perturbation the physical and biological systems can tolerate without undergoing major changes that have serious implications for sustainability. We need to remember that human society plays a key role in deciding what materials we make, why and how we use them, and what degree of care and attention we give to identifying, managing, and avoiding dangers to ourselves and our environment. Figure 2.8 brings these additional systems into the picture.⁴⁹ It can be seen that, through chemistry's central concern with the transformations of and interactions between matter, it has a leading role to play in the stewardship of materials at every stage.

The activity that follows (Section 2.3.2.3) is an example of how an educator could engage students in inquiring more about material circularity and the sustainability of material and energy supplies to better assess society's material stewardship. To demonstrate the thought process, three contexts (aluminium, cotton, and mobile phones) are illustrated first.

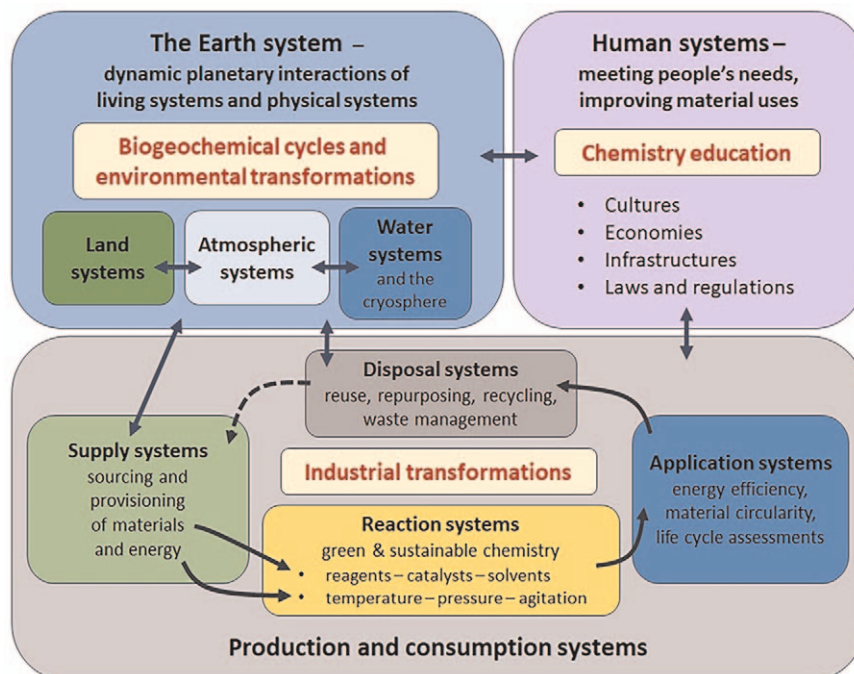


Figure 2.8 Production, consumption and disposal in the context of Earth and societal systems. Reproduced from ref. 49, 10.1039/D3SU00125C, under the terms of the CC BY 3.0 license, <https://creativecommons.org/licenses/by/3.0/>.

2.3.2.1.1 The Sustainability of Aluminium. Aluminium is the most abundant metallic element in the Earth's crust and is also one of the most highly recycled materials on the planet. A light, strong and relatively inert metal, it is widely used in food and drink containers and packaging and as structural components in vehicles and buildings. About 200 billion aluminium cans per year are used globally, with about 75% on average being recycled in Europe,⁵⁰ whereas only about half are recycled in the USA,⁵¹ and in Australia, the world's largest producer of aluminium ore and 7th largest producer of aluminium,⁵² the recycling rate was less than 60% in 2018.⁵³ Metal recovered from transport and structural applications is also extensively recycled. It is estimated that, of all the aluminium produced in history (around 1.5 billion tonnes since commercial manufacture began in the 1880s), about 75 percent is still in use today.⁵⁴

Should we consider the production and use of aluminium to be 'sustainable'? To answer this question, we need to look into both the economics and the chemistry involved.⁵⁵

- **Material circularity:** what drives the high rates of recycling of aluminium is a very strong economic factor. Because smelting aluminium ore (bauxite) requires a large amount of energy, it is expensive to

produce primary aluminium. The recycling cost for recovered metal is much lower, because re-melting uses only 5% of the energy required for primary production.⁵⁶ Used aluminium therefore retains high value, and a strong financial market exists for aluminium recycling.⁵⁷ However, the recycling economy is complicated by the chemistry: most 'aluminium' in practical use consists of alloys (*e.g.*, 'aluminium' cans are usually made of alloys typically containing 92.5–97% aluminium, as well as magnesium, manganese, chromium, and trace amounts of iron, silicon, and copper). Depending on the use, the recovered material may also be contaminated (*e.g.*, with organic wastes, paints, plastic coatings). Scrap aluminium therefore needs to be assessed, chemically analysed and graded, and may require preliminary treatments before being remelted and blended with primary aluminium to create useful new materials. Over 120 Mt (million metric tonnes) of aluminium are currently produced per year, with about 35% coming from recycled metal. Annual demand for aluminium is predicted to grow to more than three times this amount by 2050.

- **Sustainability of material supplies and associated environmental footprint:** aluminium production begins with the mining of bauxite, an ore containing aluminium oxide (Al_2O_3).⁵⁸ The crude ore is first processed by crushing and washing and then heated under pressure with a solution of sodium hydroxide to produce a solution from which aluminium hydroxide ($\text{Al}(\text{OH})_3$) is precipitated, washed, and heated to provide purified alumina. The required energy is usually derived from fossil fuels. The residue from digesting the crude bauxite is a highly alkaline side-product, mainly containing red iron oxide, as well as compounds of other elements present in the source ore. Over 160 million tonnes of this toxic material, known as 'Red Mud', was produced alongside 126 Mt of purified alumina in 2018. Over more than a century, the environmentally safe disposal of the Red Mud generated has been a major, ongoing challenge which has still not been adequately solved globally.^{59–61}
- **Sustainability of energy supplies and associated environmental footprint:** the smelting of the purified alumina⁶² involves the electrolysis of Al_2O_3 in a mix of molten cryolite and calcium fluoride at over 950 °C, reducing the oxide to Al metal, which is run off in a molten state. The electrochemical cell uses carbon electrodes and during the reaction these are oxidised, releasing about 13 tonnes of CO_2 per tonne of Al produced. The reaction conditions also create a range of other gaseous by-products that, along with CO_2 , are emitted into the atmosphere. These include volatile perfluorocarbons such as CF_4 and C_2F_6 with greenhouse gas ratings significantly higher than for CO_2 itself.⁶³ The electrochemical step is highly energy-intensive (about 15 kWh of electricity is required to produce 1 kg of Al) and this electric energy alone accounts for about 20–40% of the overall cost of aluminium production, depending on the location of the smelter and source of electricity.

Globally, about half of the electrolysis for aluminium production involves the use of hydroelectricity, while carbon-based fuels account for 45%, adding another source of greenhouse gas emissions to the footprint of aluminium production.

Thus, despite the high rate of recycling of aluminium, its current production overall is far from sustainable, since it is extremely energy-intensive, with much of the energy coming from carbon-based fuels. In addition, the production generates by-products with environmental impacts on land, water, and atmosphere. As the international aluminium industry itself acknowledges,⁶⁴ while the public currently hold the view that aluminium is a “green” and “environmentally friendly” material, the industry needs to take active steps in energy reduction if it is to avoid negative impacts on aluminium’s “brand”.

2.3.2.1.2 The Sustainability of Cotton. Cotton is the most widely used natural fibre in textiles, with global production of 26.1 million tonnes in 2018, corresponding to more than 81% of the natural fibres and about 23% of natural and synthetic fibres altogether.^{65,66} Because cotton is ‘natural’ and ‘renewable’, should it be regarded as ‘sustainable’? We can ask the same questions as for aluminium to explore this: what resources are used in sourcing, using, and disposing of cotton, and what are the side products and environmental impacts along the pathway, including from any recycling?⁵⁵

- **Sustainability of material supplies:** the feedstock requirements and environmental footprint of cotton farming are substantial. The sourcing stage consumes about 16% of global insecticides, 4% of the world’s nitrogen-based fertilisers, and 3% of the world’s irrigation water, with 3000–7000 L of water needed to produce one kg of the cotton lint from which cotton fibres are spun.⁶⁷ The amount of water needed varies substantially because the availability of water in different countries, due to environmental or political reasons, plays a significant role in which practices are employed.
- **Sustainability of energy supplies:** mostly derived from oil-based fuels, energy is used to operate machinery for ploughing, planting, irrigation, fertiliser application, crop spraying, harvesting, and for materials and labour transport. Annual cotton production globally generates emissions of around 220 million tonnes of CO₂ equivalent, or about 0.8% of the global emissions total.⁶⁸
- **Environmental footprint:** spinning cotton yarn and manufacturing cotton cloth also produces substantial amounts of CO₂ and wastewater. Particularly significant are the chemical treatments employed to make the finished material. These include bleaching and dyeing processes and the addition of oil and water repellents; anti-stain, anti-wrinkle, and anti-shrinking agents; flame-retardants; plasticisers; biocidal

substances; stabilisers; and softeners for surface feel and other effects. About 5 million tonnes per year of dyes, pigments, and finishing chemicals are used across all textiles,⁶⁹ with not all chemicals tested for human safety before usage.

- **Material circularity:** these same chemicals complicate the sorting of post-consumer clothing for fibre recovery and recycling and pose challenges for the environment, since the leaching of additives and their soluble degradation products from waste sites contaminates land and water. Recycling is also made difficult by the fact that many textiles are blends of different fibres – often a combination of natural and synthetic fibres – which may need to be sorted and separated. Only 20% of textiles are collected for reuse or recycling globally, rather than going to landfill or incineration.^{70,71}

Thus, the fact that cotton is a natural product that can be grown does not automatically define it as ‘sustainable’. The whole pathway of its production, use, and disposal needs to be considered, and the interactions of material and energy inputs and outputs with the environment need to be assessed on a case-by-case and step-by-step basis.⁷²

2.3.2.1.3 The Sustainability of Smartphones. Smartphones are iconic examples of technology in the 21st century, with more than 7 billion in circulation and around 4.5 billion in active use in 2023.²² These devices are a triumph of chemistry, physics, materials science, engineering, and information and communication technology. They allow us to communicate by voice, video, and text to anyone, anywhere in the world, who has compatible hardware, software, and connectivity and to seek, transmit, and process information on a vast scale.

How sustainable are smartphones? We can explore a number of dimensions of this question:

- **Sustainability of material supplies and associated environmental footprint:** in total, over 70 elements are used in different smartphone models. They may be present either in the elemental state (*e.g.*, gold contacts, copper wires) or, more often, as compounds or mixtures (*e.g.*, transistors, glass and ceramic screens, solders, batteries).⁷³ Usually at least 30 elements are present in any individual handset, including some whose known sources are likely to be exhausted or severely depleted within a century,⁷⁴ or are considered ‘conflict’ minerals, such as cobalt,⁷⁵ sourced from socio-politically volatile regions of the world. We must also take into account the physical infrastructures that, while invisible to the user, are essential to support the operation of smartphones. These include a wide array of materials in the cables, servers, routers, switches, satellites, signal broadcasters, relays, and receivers necessary to provide wired and wireless network communication and data storage functions.

- **Sustainability of energy supplies and associated environmental footprint:** life cycle assessments indicate that a smartphone typically contributes an aggregate in the range of about 50–100 kg CO₂-equivalent to greenhouse gas emissions, based on a 3-year lifetime, mostly from the production phase but also from transportation costs and then during use. This carbon footprint increases by more than 40 kg CO₂-equivalent when the allocated impact from operating network and data centre usage is included.^{76–78} Power consumption in recharging the phone battery depends on the level of use, but typically is of the order of 1 kW per year. This modest-sounding amount sums to more than 1 Tw hours per year for all the smartphones in active use. In addition, data centres and data transmission networks each account for 1–1.5% of global electricity use,⁷⁹ and with the emerging harnessing of computing power for artificial intelligence applications,⁸⁰ this percentage is expected to significantly increase.
- **Material circularity:** there is a widespread view that smartphones are designed to become quickly obsolete and to be difficult to repair, refurbish, and recycle.⁸¹ Although smartphones contain valuable metals such as gold, copper, silver, palladium, and other recyclable components, the vast majority that are no longer used are either consigned to hibernating in the back of a drawer or discarded to become ‘e-waste’, most of which ends up in landfills. The global recycling rate of mobile phones is under 10%, attributed to a combination of technology challenges and poor economic and social incentives.^{82–84}

Box 2.8 provides a series of questions to guide students in exploring the sustainability of smartphones.

Box 2.8 Questions for student discussion – sustainability of smartphones.

These questions could be used with students investigating the sustainability of smartphones with respect to matter and energy requirements, associated environmental footprint, and material circularity:

- Which elements and compounds are used in manufacturing smartphones, where are they sourced, and which ones are likely to see shortages and become bottlenecks as smartphone use continues to increase worldwide?
 - The ‘endangered’ elements infographic activity in Section 2.3.1.4 also presented one way that students could explore these questions.
- Which sources of energy are used in constructing, maintaining, and running the internet? How sustainable are they?
- What are the main environmental outputs and impacts associated with the stages of smartphone production and use?

2.3.2.2 Connections to the Chemistry Curriculum

The three examples just cited provide excellent curriculum-relevant, real-world contexts and case studies to investigate the sustainability of a material, and thus its material stewardship. They all illustrate that, in view of increasing demand for materials of all kinds and the finite amounts of matter available to us, humanity has no option but to learn how to conserve the supplies to the best possible extent. This conservation must include:

- reducing demand – consider again *The Limits to Growth* report¹⁴ – (Section 2.1)
- lowering waste in manufacture, distribution, and use, and
- recovering and recycling as much as possible.

Globally, many secondary and undergraduate chemistry curricula have taken steps to include investigating the greenness and sustainability of chemical processes or products. In many curricula, you can find the 12 Principles of Green Chemistry, first proposed by Anastas and Warner⁸⁵ in 1998 (Chapter 1). These principles provide an approach for educators to compare traditional chemical synthesis with efficient and environmentally benign processes for extraction and recovery. Increasingly, curricula are incorporating discussion of the transition from a linear to a circular economy, encouraging students to analyse and evaluate responses to chemistry-based scenarios and case studies.

Currently, the topic of material stewardship is not regularly seen in state and national curriculum documents, but it is a logical extension of the curricula integration approach started with the green chemistry principles.

2.3.2.3 Activity: Researching an Example of Material Stewardship

The earlier descriptions of the aluminium, cotton, and smartphone scenarios demonstrate that investigating the sustainability of a material and material stewardship involves more than just a few chemical equations and stoichiometric calculations. To better represent the chemical basis of sustainability, or to argue how chemistry needs to contribute centrally to the overall stewardship of the planet's resources, students need more time and ample space to express their conceptual understanding of these complex issues. Therefore, a reasonable form of student response would be in the form of an essay or case-study report.

In an essay, students could meaningfully rationalise how material stewardship also presents socio-economic and technical challenges for society:

- Innovative technologies that challenge common wisdom and practice will be needed to make material circularity possible.
- Economic systems will need incentives to take up circular models but do this in a manner that does not prioritise the 'economic risk' as the basis for changing how a material is produced, distributed, or utilised.
- Individuals and societies need to change behaviour and culture to embrace the new models, but again do this in a manner that does not

present the individual as ‘the cause and the solution’, without stressing the shared responsibilities of society, government, and industry.

Box 2.9 presents an essay assignment for students on material stewardship, with a global essay competition⁸⁶ run since 2023 as an example.

Box 2.9 Assignment – student essay on a material stewardship theme.

In 2023, the International Organization for Chemical Sciences in Development (IOCD), in collaboration with the Royal Society of Chemistry (RSC), launched an annual global essay competition, titled “Young Voices in the Chemical Sciences,” for young people (35 years and under) on the role of the chemical sciences in sustainability.⁸⁵

In an essay, students are encouraged to highlight chemical sciences contributions to addressing sustainable development challenges, and holistically reflect on the intersection of science, society, and policy aspects, instead of just provide an account of the scientific advance. To provide direction to students, the yearly competition has had an annual theme:

- 2023: How can the chemical sciences lead the stewardship of the Earth’s element resources?
- 2024: How can the chemical sciences contribute to ‘decarbonising’ the production of energy and to eliminating the generation or release of greenhouse gasses from large-scale manufacturing and agricultural processes?
- 2025: From waste to wealth: how chemical sciences can sustainably transform waste into valuable products.

Educators setting their students a material stewardship- or sustainability-themed essay may wish to use either their own prompting question or one of these question themes. They could even find the question theme being used for that year and consider encouraging their students to enter.

To provide further guidance, an educator may wish to direct students to consider one or more of the sub-themes outlined earlier for aluminium, cotton, and smartphones, specifically:

- What is the sustainability of the material supplies/precursors needed for this chemical process/product/innovation?
- What is the sustainability of the energy supplies needed for this chemical process/product/innovation?
- What are the associated environmental impacts of this chemical process/product/innovation, its material precursors, and its lasting impact at end-of-life?
- What measure of material circularity does the chemical process/product/innovation have?
- Where along the transition from a linear economy to a circular economy would this be placed?

It is understandable that inviting chemistry students to argue and take positions on these emotive and socio-political considerations will initially prove challenging to an educator wanting to ‘stick to the chemistry’. However, consider this – would a chemistry assessment task that, instead of just knowledge questions, contained a few questions about ethics and politics be seen as *less* motivating by students? *Less* engaging? Now consider that when the student realises that these are not questions about ethics and politics but actually are questions about how *chemistry knowledge is vital* to the manner in which we need to approach these ethical and political considerations, this student is beginning to grasp the importance of chemistry’s central role in the stewardship of the planet’s finite resources. Topics relating to ethics are explored in other chapters, but especially in Chapter 8 on sustainability ethics.

2.4 Closing Thoughts – A Sustainability Framework for Chemistry

Several concepts, orientations, frameworks, and tools that have emerged since the mid-20th century show that chemistry is already making progress with respect to taking on the responsibilities inherent in this goal of material stewardship. For example, as discussed in Chapter 1, green chemistry offers guidelines for making reactions clean and efficient, and circular chemistry takes further steps towards designing circular processes with optimum retention of material value. One-world chemistry draws on the recognition that human and animal health and the biological and physical environments of the planet are all intimately connected and requires that chemists embrace systems thinking and cross-disciplinary working skills as part of their education, research, and practice (Chapter 4). Chemists, industries, and governments are giving increasing attention to ‘benign by design’^{87,88} and ‘safe and sustainable by design’^{89,90} criteria and strategies that need to be applied, from the outset, in planning for new products.

Reference to these diverse approaches is encouraging, but their growing number and variety may also be confusing. Which are the important ones and how do they fit together to provide the chemistry section for the Operating Manual that is missing for Spaceship Earth?

Figure 2.9 builds on the model of a ‘chemistry for sustainability’ pyramid which was proposed as a way to integrate all of the relevant sustainability concepts, orientations, frameworks, and tools.⁹¹

- Material stewardship has been proposed as chemistry’s **mission** for sustainability.⁹² Its aim is to transform and use the Earth’s available stock of material resources in ways consistent with ensuring sustainability for people and for the physical and biological systems of the planet.
- Several **frameworks** set the overall direction and goals of sustainability for people and planet. For example, the Human Security Framework developed by the UN identifies seven key dimensions that are intrinsic

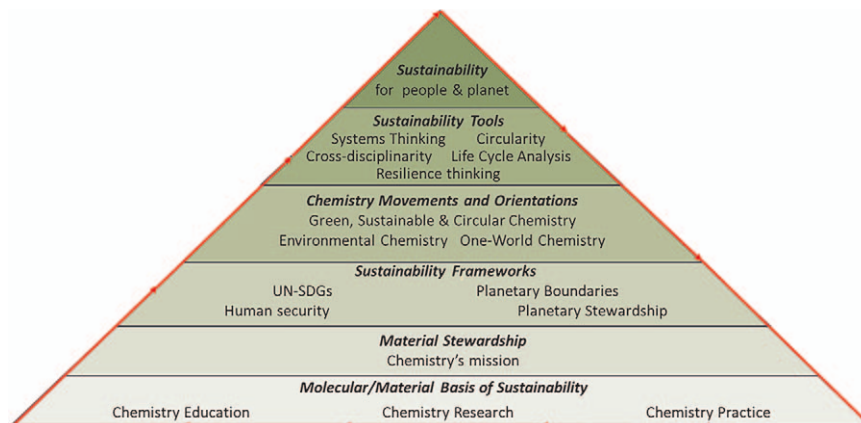


Figure 2.9 ‘Chemistry for sustainability’ pyramid. Figure drawn by Matlin.

to ‘freedom from want, freedom from fear, freedom to live in dignity’, involving security in the economic, health, food, environmental, personal, community, and political domains.^{93,94} Ways in which chemistry can contribute to all of these have been identified.⁹⁵ The Human Security Framework complements the Planetary Boundaries Framework (Chapter 6), which identifies ‘safe operating spaces’ for humanity and the UN Agenda 2030, which sets specific, time-bound Sustainable Development Goals that are on the pathway to sustainability for people and planet (Chapter 7). Chemistry’s contributions to the goals of each of these frameworks have been recognised and need to be made in the context of the overall systems picture described in Section 2.4, to ensure that solutions for human and environmental security also respect the limits of long-term sustainability of the planet’s material resources and ensure their continuing availability for future generations, building in the adoption of material stewardship.

- Further guidance comes from specific **movements and orientations** that chemists have developed, including environmental, green, sustainable, one-world, and circular chemistry. In addition, the concept of resilience is an important factor. Resilience is used in the environmental sciences to discuss the adaptive capacity of ecological systems placed under stress. There are many ways in which chemistry can contribute to increasing resilience.⁹⁶
- **Tools** are available to assist chemists in making the required contributions to the frameworks and the sustainability goals they define. These tools are shared with other disciplines and are widely recognised and adopted as part of common approaches to defining and overcoming sustainability challenges. As discussed here, systems thinking (Chapter 4) is key to understanding the breadth of interactions that take place in the nexus of production and consumption systems and Earth and societal systems. Working in this nexus, chemists need to embrace

cross-disciplinary working and, in collaboration with many other disciplines, use the methods of material circularity and life cycle analysis (Chapter 5) to define sustainable pathways.

- The pyramid sits on a platform that is the discipline of chemistry itself, which provides the **molecular/material basis of sustainability** through all its aspects of education, research, and practice.

The ‘chemistry for sustainability’ pyramid illustrates that all the frameworks, tools, movements, and orientations need to be taken together and their use integrated for chemists to develop systems for material transformations that are on pathways to sustainability. In this sense, the pyramid exemplifies the important principle that sustainability is an emergent property of the whole system and not a property of individual components of the system.⁹⁷

References

1. S. A. Matlin and B. M. Abegaz, in *The Chemical Element: Chemistry's Contribution to Our Global Future*, ed. J. Garcia-Martinez and E. Serrano-Torregrosa, Wiley-VCH, Weinheim, 2011, ch. 1, pp. 1–70.
2. W. Steffen, W. Broadgate, L. Deutsch, O. Gaffney and C. Ludwig, *Anthropocene Rev.*, 2015, 2(1), 81.
3. E. Elhacham, L. Ben-Uri, J. Grozovski, Y. M. Bar-On and R. Milo, *Nature*, 2020, 588, 442.
4. S. Derouin, Antarctic study shows how much space dust hits Earth every year, 2021, <https://www.scientificamerican.com/article/antarctic-study-shows-how-much-space-dust-hits-earth-every-year/> (accessed August 2025).
5. NASA Jet Propulsion Laboratory, Herschel Helps Solve Mystery of Cosmic Dust Origins, <https://www.jpl.nasa.gov/news/herschel-helps-solve-mystery-of-cosmic-dust-origins/> (accessed August 2025).
6. European Space Agency, The curious case of Earth's leaking atmosphere, <https://sci.esa.int/web/cluster/-/58028-the-curious-case-of-earth-s-leaking-atmosphere> (accessed August 2025).
7. K. J. Zahnle and D. C. Catling, How planets lose their atmospheres, 2009, <https://www.scientificamerican.com/article/how-planets-lose-their-atmospheres/> (accessed August 2025).
8. D. Coffey, Is Earth expanding or shrinking, 2022, <https://www.livescience.com/is-earth-expanding-or-shrinking> (accessed August 2025).
9. C. H. Langmuir and W. Broecker, in *How to Build a Habitable Planet: The Story of Earth from the Big Bang to Humankind*, revised and expanded edition, Princeton University Press, Princeton, NJ, 2012.
10. A. E. Stevenson, Speech to the Economic and Social Council of the United Nations, Geneva, Switzerland, 1965, https://www.adlaitoday.org/articles/connect2_geneva_07-09-65.pdf (accessed August 2025).
11. B. Ward, *Spaceship Earth*, Columbia University Press, New York, NY, 1966.
12. (a) K. E. Boulding, in *Environmental Quality in a Growing Economy*, ed. H. Jarrett, Resources for the Future/Johns Hopkins University Press,

- Baltimore, MD, 1966, pp. 3–14, http://arachnid.biosci.utexas.edu/courses/THOC/Readings/Boulding_SpaceShipEarth.pdf (accessed August 2025); (b) see also: E. Barbier and J. Burgess, Economic Principles for “Spaceship Earth”, Resources, 2017, <https://www.resources.org/archives/economic-principles-for-spaceship-earth/> (accessed August 2025).
13. (a) R. B. Fuller, *Operating Manual for Spaceship Earth*, Southern Illinois University, Carbondale, IL, 1969. https://designsciencelab.com/resources/OperatingManual_BF.pdf (accessed August 2025); (b) see also: R. Buckminster Fuller Collection, Stanford University Libraries, Stanford, CA, <https://exhibits.stanford.edu/bucky/feature/what-is-spaceship-earth> (accessed August 2025).
 14. (a) D. H. Meadows, D. L. Meadows, J. Randers and W. W. Behrens, *The Limits to Growth*, Universe, New York, NY, 1972; (b) see also: Club of Rome – Publications, <https://www.clubofrome.org/publications/?filter=reports-to-cor> (accessed August 2025).
 15. (a) V. Liegey and A. Nelson, *Exploring degrowth: A critical guide*, Pluto Press, London, 2020; (b) R. Costanza, *Nature*, 2023, **624**, 519.
 16. International Energy Agency (IEA), *Net Zero by 2050. A Roadmap for the Global Energy Sector*, IEA, Paris, 2021, <https://www.iea.org/reports/net-zero-by-2050> (accessed August 2025).
 17. R. E. Smalley, *MRS Bull.*, 2005, **30**, 412.
 18. Solar energy, Explaining Science, 2019, <https://explainingscience.org/2019/03/09/solar-energy/> (accessed August 2025).
 19. C. Hoffs, Just and Sustainable Solutions for the Mining and Recycling of Rare Earth Elements in Wind Turbines, 2022, <https://blog.ucs.org/charlie-hoffs/just-and-sustainable-solutions-for-the-mining-and-recycling-of-rare-earth-elements-in-wind-turbines/> (accessed August 2025).
 20. C. Woodford, What is Photoelectricity?, 2023, <https://www.explainthatstuff.com/how-photoelectric-cells-work.html#definition> (accessed August 2025).
 21. Energy Storage, Union of Concerned Scientists, 2021, <https://www.ucs.org/resources/how-energy-storage-works> (accessed August 2025).
 22. N. Kumar, How Many People Own Smartphones (2025): Worldwide Data, Demandsage, 2024, <https://www.demandsage.com/smartphone-users/> (accessed August 2025).
 23. Future trends in biofuels, Biofuels International, 2021, <https://biofuels-news.com/news/future-trends-in-biofuel/> (accessed August 2025).
 24. Y. Sokona, Y. Mulugetta, F. Kaboub, M. Tesfamichael, N. Hällström, M. Stilwell, M. Adow and C. Besaans, *Just Transition: A Climate, Energy and Development Vision for Africa*, Independent Expert Group on Just Transition and Development, 2023, https://justtransitionafrica.org/wp-content/uploads/2023/05/Just-Transition-Africa-report-ENG_single-pages.pdf (accessed August 2025).
 25. What is Hydrogen? Australian Climate Council, 2023, <https://www.climatecouncil.org.au/resources/what-is-hydrogen/> (accessed August 2025).
 26. A. Delpuech, *Who Benefits from Tunisia’s Green Hydrogen Strategy?* Arab Reform Initiative, Tunis, 2022, <https://s3.eu-central-1.amazonaws.com/>

- storage.arab-reform.net/ari/2022/12/19152041/2022-12-20-EN-Green-Hydrogen-HBS-FINAL.pdf (accessed August 2025).
27. C. Porteous, B. Godfrey and A. Finkel, *Taking charge: the energy storage opportunity for Australia*, Australian Government, Office of the Chief Scientist – Occasional Paper, 2018, <https://www.chiefscientist.gov.au/sites/default/files/Energy-storage-paper.pdf> (accessed August 2025).
 28. International Energy Agency (IEA), *Global Hydrogen Review 2023*, IEA, Paris, 2023, <https://www.iea.org/reports/global-hydrogen-review-2023> (accessed August 2025).
 29. S. A. Matlin, G. Mehta, H. Hopf and A. Krief, *Nat. Chem.*, 2016, **8**, 393.
 30. S. A. Matlin, G. Mehta, H. Hopf and A. Krief, *Eur. J. Inorg. Chem.*, 2019, **39-40**, 4170.
 31. Endangered elements, American Chemical Society, <https://www.acs.org/green-chemistry-sustainability/research-innovation/endangered-elements.html> (accessed August 2025).
 32. D. Chattopadhyay, *Resonance*, 2022, **17**, 79.
 33. European Commission, *European Critical Raw Materials Act*, European Commission, Brussels, 2023, https://ec.europa.eu/commission/presscorner/api/files/attachment/874736/Factsheet_GD_European%20Critical%20Raw%20Materials%20Act%20.pdf (accessed August 2025).
 34. Strategic materials, U.S. Defense Logistics Agency, USA, 2018, <https://www.dla.mil/Strategic-Materials/> (accessed August 2025).
 35. House of Commons, *Strategically important metals, Fifth Report of Session 2010–12*, UK House of Commons Science and Technology Committee, London, 2011, <https://publications.parliament.uk/pa/cm201012/cmselect/cmstech/726/726.pdf> (accessed August 2025).
 36. S. Bruce, B. Delaval, A. Moisi, J. Ford, J. West, J. Loh and J. Hayward, *Critical Energy Minerals Roadmap*, CSIRO, Canberra, 2021, https://www.csiro.au/-/media/Do-Business/Files/Futures/Critical-energy-minerals-roadmap/21-00041_MR_REPORT_CriticalEnergyMineralsRoadmap_WEB_210420.pdf (accessed August 2025).
 37. European Commission: Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, M. Grohol and C. Veeh, *Study on the critical raw materials for the EU 2023 – Final report*, Publications Office of the European Union, 2023, <https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1> (accessed August 2025).
 38. Commonwealth of Australia, *Critical Minerals Strategy 2023–2030*, Australian Government Department of Industry, Science and Resources, Canberra, 2023, <https://www.industry.gov.au/sites/default/files/2023-06/critical-minerals-strategy-2023-2030.pdf> (accessed August 2025).
 39. C. Reichl and M. Schatz, *World Mining Data*, Federal Ministry of Sustainability and Tourism, Vienna, 2019, <https://www.world-mining-data.info/wmd/downloads/PDF/WMD2019.pdf> (accessed August 2025).
 40. United States Geological Survey, *Mineral Commodity Summaries 2023*: U.S. Geological Survey, Reston VA, 2023, <https://pubs.usgs.gov/periodicals/mcs2023/mcs2023.pdf> (accessed August 2025).

41. International Energy Agency (IEA), *The Role of Critical Minerals in Clean Energy Transitions*, IEA, Paris, 2021, <https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions> (accessed August 2025).
42. N. Sönnichsen, Global oil production 1998–2023, Statista, 2024, <https://www.statista.com/statistics/265229/global-oil-production-in-million-metric-tons/> (accessed August 2025).
43. Samuele, Artistic Periodic Table of Elements, International Union of Pure and Applied Chemistry, 2019, <https://iupac.org/100/pt-challenge-entry/artistic-periodic-table-of-elements/> (accessed August 2025).
44. H. Kania and M. Saturnus, *Appl. Sci.*, 2023, **13**(3), 1.
45. G. Meylan and B. K. Reck, *Resour., Conserv. Recycl.*, 2017, **123**, 1.
46. A. Nayak, M. S. Jena and N. R. Mandre, *Miner. Process. Extr. Metall. Rev.*, 2021, **43**(5), 564.
47. (a) P. Schütte, *Resour. Policy*, 2019, **62**(C), 674–689; (b) M. Agrawal, R. Singh, M. Ranitović, Z. Kamberovic, C. Ekberg and K. K. Singh, *Sustainable Materials and Technologies*, 2021, **29**, e00323.
48. S. Kaza, L. C. Yao, P. Bhada-Tata and F. Van Woerden, *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050*, Urban Development, World Bank, Washington, DC, 2018, <http://hdl.handle.net/10986/30317> (accessed August 2025).
49. S. A. Matlin, G. Mehta, S. E. Cornell, A. Krief and H. Hopf, *RSC Sustainability*, 2023, **1**, 1704.
50. Recycling rate of aluminium cans in Europe in 2020, by country, Statista, Imperial College London, 2023, <https://www.statista.com/statistics/239315/recycling-quota-of-aluminum-cans-in-europe/> (accessed August 2025).
51. Consumer recycling rate of domestic aluminium can scrap in the United States from 2011 to 2018, Statista, Imperial College London, 2023, <https://www.statista.com/statistics/1055981/consumer-recycling-rate-aluminum-can-scrap-us/> (accessed August 2025).
52. Major countries in worldwide bauxite mine production in 2022, Statista, Imperial College London, 2023, <https://www.statista.com/statistics/264964/production-of-bauxite/> (accessed August 2025).
53. Australian Capital Territory Government, *Aluminium recycling – waste sorted*, ACT Government, Canberra, 2018, https://www.cityservices.act.gov.au/__data/assets/pdf_file/0006/1368618/NOWaste-Aluminum-Factsheet_Update-March-2022_ACCESS.pdf (accessed August 2025).
54. Recycling, International Aluminium Institute, London, 2023, https://international-aluminium.org/work_areas/recycling/ (accessed August 2025).
55. S. A. Matlin, G. Mehta, H. Hopf, A. Krief, L. Keßler and K. Kümmerer, *Sustainable Chem. Pharm.*, 2020, **17**, 100312.
56. World aluminium recycling factsheet, International Aluminium Institute, London, 2020, <https://international-aluminium.org/resource/aluminium-recycling-fact-sheet/> (accessed August 2025).

57. D. Raabe, D. Ponge, P. J. Uggowitzer, M. Rosche, M. Paolantonio, C. Liu, H. Antrekowitsch, E. Kozeschnik, D. Seidmann, B. Gault, F. De Geuser, A. Deschamps, C. Hutchinson, C. Liu, Z. Li, P. Prangnell, J. Robson, P. Shanthraj, S. Vakili, C. Sinclair and S. Pogatscher, *Prog. Mater. Sci.*, 2022, **128**, 100947.
58. D. Brough and H. Jouhara, *Int. J. Thermofluids*, 2020, **1-2**, 100007.
59. M. A. Khairul, J. Zanganeh and B. Moghtaderi, *Resour., Conserv. Recycl.*, 2019, **141**, 483.
60. A. M. Donoghue, N. Frisch and D. Olney, *J. Occup. Environ. Med.*, 2014, **56**(5 Suppl. 1), S12.
61. T. Hertel and Y. Pontikes, *J. Cleaner Prod.*, 2020, **258**, 120610.
62. M. Obaidat, A. Al-Ghandoor, P. Phelan, R. Villalobos and A. Alkhalidi, *Sustainability*, 2018, **10**, 1216.
63. T. A. Aarhaug and A. P. Ratvik, *JOM*, 2019, **71**, 2966.
64. CM Group, *An assessment of global megatrends and regional and market sector growth outlook for aluminium demand*, Glenelg, Australia, 2020, https://international-aluminium.org/wp-content/uploads/2024/03/cm_2050_outlook_for_al_demand_20200528_4wycD18.pdf (accessed August 2025).
65. Food and Agriculture Organization of the United Nations (FAO), *Recent trends and prospects in the world cotton market and policy developments*, FAO, Rome, 2021, <http://www.fao.org/3/cb4589en/cb4589en.pdf> (accessed August 2025).
66. Textile Exchange, *Materials Market Report*, Textile Exchange, Lamesa TX, December 2023, <https://textileexchange.org/knowledge-center/reports/materials-market-report-2023/> (accessed August 2025).
67. Food and Agriculture Organization of the United Nations (FAO), *Measuring sustainability in cotton farming systems: towards a Guidance Framework*. FAO, International Cotton Advisory Committee, Rome, 2015, <http://www.fao.org/3/a-i4170e.pdf> (accessed August 2025).
68. G. Famworth, *Cool Cotton*. The Soil Association, Bristol, 2015, <https://www.soilassociation.org/media/11662/coolcotton.pdf> (accessed August 2025).
69. M. M. Bomgardner, *Chem. Eng. News*, 2018, **96**(29), 28.
70. S. Abrishami, A. Shirali, N. Sharples, G. E. Kartal, L. Macintyre and O. Doustdar, *Text. Res. J.*, 2024, **94**(23–24), 2815.
71. S. Moazzem, L. Wang, F. Daver and E. Crossin, *Resour., Conserv. Recycl.*, 2021, **166**, 105338.
72. M. Boström and M. Micheletti, *J. Consum. Policy*, 2016, **39**, 367.
73. B. Rohrig, *ChemMatters*, American Chemical Society, 2015, <https://www.acs.org/content/dam/acsorg/education/resources/highschool/chemmatters/documents/smartphones-smart-chemistry.pdf> (accessed August 2025).
74. D. Cole-Hamilton, *Elements in danger*, Royal Society of Chemistry, London, 2019, <https://www.rsc.org/news/2019/january/elements-in-danger> (accessed August 2025).
75. Amnesty International, *“This is what we die for”: Human rights abuses in the Democratic Republic of the Congo power the global trade in cobalt*,

- Amnesty International, London, 2016, <https://www.amnesty.org/en/documents/afr62/3183/2016/en/> (accessed August 2025).
76. M. Ercan, J. Malmödin, P. Bergmark, E. Kimfalk and E. Nilsson, *4th International Conference on ICT for Sustainability*, Atlantis Press, Amsterdam, 2016, DOI: 10.2991/ict4s-16.2016.15.
 77. A. Joshi, A. Gupta, S. Verma, A. R. Paul, A. Jain and N. Haque, *IOP Conf. Ser.: Earth Environ. Sci.*, 2021, **795**, 012028.
 78. L.-P. P.-V. P. Clément, Q. E. S. Jacquemotte and L. M. Hilty, *Environ. Impact Assess. Rev.*, 2020, **84**, 106416.
 79. International Energy Agency (IEA), *Data Centres and Data Transmission Networks*, IEA, Paris, 2024, <https://www.iea.org/energy-system/buildings/data-centres-and-data-transmission-networks> (accessed August 2025).
 80. Organisation for Economic Co-operation and Development (OECD), *Harnessing the power of AI and emerging technologies: Background paper for the CDEP Ministerial meeting*, *OECD Digital Economy Papers*, No. 340, OECD Publishing, Paris, 2022, https://www.oecd.org/en/publications/2022/11/harnessing-the-power-of-ai-and-emerging-technologies_c74e020c.html (accessed August 2025).
 81. M. Cordella, F. Alfieri, C. Clemm and A. Berwald, *J. Cleaner Prod.*, 2021, **286**, 125388.
 82. M. J. Welfens, J. Nordmann and A. Seibt, *J. Cleaner Prod.*, 2016, **132**, 108.
 83. N. S. Prabhu and R. Majhi, *Waste Manage. Res.*, 2023, **41**, 18.
 84. T. B. Yahya, N. M. Jamal, B. Sundarakani and S. Z. Omain, *Recycling*, 2021, **6**(2), 30.
 85. P. T. Anastas and J. C. Warner, *Green Chemistry: Theory and Practice*, Oxford University Press, New York, 1998.
 86. IOCD Annual Essay Competition: Young Voices in the Chemical Sciences for Sustainability, http://www.iocd.org/v3_site/Sources/essay_competition.html (accessed August 2025).
 87. *Benign by Design Chemistry*, ed. P. T. Anastas and C. A. Farris, ACS Publications, Washington, DC, 1994.
 88. A. King, *Anthropocene Magazine*, 2018, <https://www.anthropocenemagazine.org/2018/09/benign-by-design/> (accessed August 2025).
 89. C. Caldeira, L. R. Farcas, I. Garmendia Aguirre, L. Mancini, D. Tosches, A. Amelio, K. Rasmussen, H. Rauscher, J. R. Sintes and S. Sala, *Safe and sustainable by design chemicals and materials: Framework for the definition of criteria and evaluation procedure for chemicals and materials*, EUR 31100 EN, Publications Office of the European Union, Luxembourg, 2022, <https://publications.jrc.ec.europa.eu/repository/handle/JRC128591> (accessed August 2025).
 90. CEFIC, *Safe and Sustainable-by-Design: A Guidance to Unleash the Transformative Power of Innovation*, CEFIC, Brussels, 2023, <https://cefic.org/a-solution-provider-for-sustainability/safe-and-sustainable-by-design/> (accessed August 2025).
 91. J. M. Whalen, S. A. Matlin, T. A. Holme, J. J. Stewart and P. G. Mahaffy, *ACS Sustainable Chem.*, 2022, **10**, 12933.

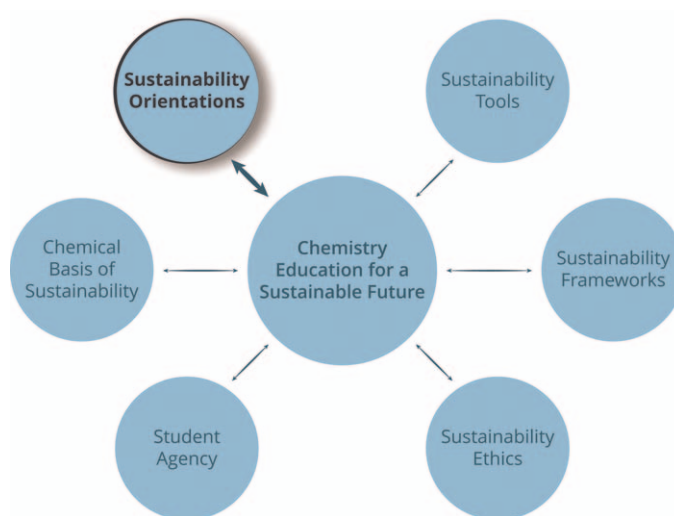
92. S. A. Matlin, S. E. Cornell, K. Kümmerer, P. G. Mahaffy and G. Mehta, *RSC Sustainability*, 2025, **3**, 804.
93. United Nations Development Programme, *Human Development Report 1994*, United Nations Development Programme, New York, 1994, <https://www.un-ilibrary.org/content/books/9789210576550> (accessed August 2025).
94. United Nations Trust Fund for Human Security, Agenda 2030, <https://www.un.org/humansecurity/agenda-2030/> (accessed August 2025).
95. S. A. Matlin, A. Krief, H. Hopf and G. Mehta, *Angew. Chem., Int. Ed.*, 2021, **60**(49), 25610.
96. G. Mehta, S. E. Cornell, A. Krief, H. Hopf and S. A. Matlin, *R. Soc. Open Sci.*, 2022, **9**, 212004.
97. F. Ceschin and I. Gaziulusoy, *Des. Stud.*, 2016, **47**, 118.

CHAPTER 3

Orienting Chemistry Towards Sustainability[†]

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3.1 Opening Thoughts

Chemistry is the science dealing with materials and their transformation. Because chemistry is the science of materials, in a sense, everything around and in us is “chemistry”. It is the basis of our high quality of life. It is the science that led to or enabled the creation and successful development of many industrial sectors, such as materials, consumer products, and health care, and supported the development of others, *e.g.*, energy, mobility, and agriculture. In turn, these sectors are composed of many different industries, such as pharmaceuticals, pesticides, plastics, containers and packaging, metals and mining, and more generally, the chemical industry.¹ All of them use chemicals to create or improve the performance or durability of their products. For example, per- and polyfluoroalkyl substances (PFAS) are a large class of chemicals found in flame retardants, packaging, cosmetics, and many other products (see Section 3.3).

Products such as computers, cars, and mobile phones are manufactured by other industries, including the automotive, electronics, textiles, paper, plastics, pesticides, and the personal care and cosmetics industries. However, these other industries use products of the chemical industry as building blocks for their products and additives to modify properties. For example, thermoplastic polymer granules are remolded to form new products. Often, they are mixed with additives such as flame retardants and optical brighteners to produce synthetic fibers as basic constituents of textiles.

For too long, pollution of the environment, as evidenced by visible exhausts into the air, chemical odors, or river water colored by synthetic dye production, was seen as a positive indication of economic growth and an improved standard of living. In other words, the success story of chemistry is at the same time linked to the acceleration of resource use, waste generation, health and ecosystem impact, and environmental pollution. In her seminal book *Silent Spring*, published in 1962, Rachel Carson addressed the issues resulting from the introduction of chemicals into the environment, leading to the birth of the modern environmental movement.² Nowadays one of the most important sources of environmental pollution by chemicals is the products themselves, adding a double burden to less developed countries where exhaust and effluent treatment is often not (yet) in place.

This chapter examines the evolution of the chemistry enterprise from a synthesis only focus linked to waste generation toward a greener and more sustainable mindset. Green chemistry, circular chemistry, and sustainable chemistry are the approaches involved in protecting human health, resources, the environment, and the planet on the path to a more sustainable future.

3.2 Background

This section describes the progression from just delivering products to addressing the resulting challenges, such as waste, environmental pollution,

impacts on human health and other organisms, and resource depletion. It introduces measures taken to minimize waste and, even more importantly, how to prevent it in the first place (pollution prevention, green chemistry, circular chemistry, and sustainable chemistry).

3.2.1 Chemical Waste

No chemical reaction results in 100% of the desired product. There is always waste consisting of byproducts, solvents, and unused starting materials and reagents. To valorize such waste, the components have to be separated and upgraded. They could be reused (*e.g.*, as starting materials or solvents) in the same reaction or in the synthesis of another product. However, if the chemicals have similar properties, the separation and upgrading of the components of the waste can be challenging, and additional waste may be generated from the separation process itself.

Using chemical waste as a resource was one of the starting points of organic industrial chemistry. For example, the production of “illuminating gas”, made from distilling coal in a retort, resulted in a residue called coal tar. This residue was used to preserve wood, such as railroad ties, among other applications. Early organic chemists, such as Friedlieb Ferdinand Runge, August Wilhelm Hofmann, and William Henry Perkin, isolated aromatic compounds from the tar. One of these, aniline, was the starting material for the first synthetic dyes. Mauveine (“aniline purple”), one of these dyes, was the foundation of the so-called coal tar dye industry, which in turn was the beginning of organic industrial chemistry. The synthetic dyes were much more colorful and stable than natural ones (Figure 3.1), the reason for this unprecedented success story. However, after World War II, “fossil oil” (petroleum) was used as a major resource for organic chemistry in the chemical industry.^{3,4}

In 1977, in the United States, Love Canal was spotlighted in the news. For decades, this site was used to dump chemical waste, and exposure to the toxic chemicals caused numerous health problems, including birth defects, miscarriages, epilepsy, and leukemia. This was just the start of the discovery of many chemical waste dumps and their associated hazards. The Love Canal disaster led to the passage in the United States of the Superfund Act (officially known as the Comprehensive Environmental Response, Compensation, and Liability Act), which holds industries responsible for cleaning up contaminated sites.

3.2.2 Chemical Accidents

Accidents have happened throughout the history of industrial chemistry, often resulting in many casualties and long-term health problems. Two of the most infamous are Seveso and Bhopal. In Seveso, Italy, in 1976, the accidental release of highly toxic TCDD (2,3,7,8-tetrachlorodibenzo-*p*-dioxin, “Seveso Dioxin”) caused residents to experience chloracne and severe skin



Figure 3.1 Collection of the first useful tar dyes in the historical dye collection of the Technical University of Dresden.⁵ Reproduced from ref. 5, <https://de.wikipedia.org/wiki/Teerfarben>, under the terms of the CC0 1.0 Universal license, <https://creativecommons.org/publicdomain/zero/1.0/deed.en>.

irritation, leading to long-term impacts on human health.⁶ Seveso Dioxin was a known “impurity” in Agent Orange, used as a chemical warfare agent in the Vietnam War. The 1984 Bhopal disaster at the Union Carbide India Limited pesticide plant in Bhopal, India, is considered the world’s worst industrial disaster. More than 3000 people died when methyl isocyanate was released from the plant, and more than 500 000 people were injured.

3.2.3 Environmental and Health Problems and the Rise of Environmental Chemistry

It is not just chemical accidents or dumped waste that cause direct harm to human health and the environment; there are also the unintended consequences of using certain chemicals. Unfortunately, there are plenty of examples demonstrating the negative impact of chemicals on human health and the environment.^{7,8} PFAS seem to be among the latest ones.^{9–11} However, some PFAS (perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS)) received attention in the late 1990s and early 2000s.

Often pollution and the impacts of chemicals in the environment are known but no immediate action is taken.^{12–14} In Japan, for example, Itai-itai

disease, caused by cadmium poisoning, was first reported around 1912. It took 55 years until cadmium from mining was identified as the source of this disease, which triggered severe joint and bone pain in its victims. Also in Japan, Minamata disease was first discovered in 1956. Methylmercury, which was released from a chemical factory in Minamata, Japan, bioaccumulated in shellfish and fish, which were then consumed by the local population. Mercury poisoning resulted in the death of both humans and animals over a 36-year period.

One of the best-known examples of unintended consequences is the use of chlorofluorocarbons (CFCs) in various applications, including as refrigerants. CFCs were shown to be less toxic and less flammable than earlier refrigerants, such as NH_3 and SO_2 , but they had the unintended consequence of destroying the ozone layer. Consequently, the Montreal Protocol on Substances that Deplete the Ozone Layer was adopted to phase out the use of CFCs, and chemists continue to develop refrigerants that are less harmful to the ozone layer (see Chapter 8 for more on refrigerants).

Environmental chemistry examines the fate of chemicals, including physical and chemical processes, in the natural environment. This environment includes the air, water, and soil and rocks, along with humans and other living organisms. Analytical chemistry is an essential component of environmental chemistry because it identifies and quantifies chemicals in the environment.

With the advent of gas chromatography and atomic absorption spectroscopy in the late 1960s and early 1970s, chemicals in the environment were detected and quantified at lower concentrations (parts per million, ppm). However, the monitoring of many chemicals needs more sensitive tools able to detect concentrations in the parts per billion (ppb) range or even lower. Because of their low concentration range, these chemicals are often called “micropollutants”. Liquid chromatography/tandem mass spectrometry is used to detect micropollutants in drinking water, soil, and air. One of the latest examples of micropollutants is the huge number of per- and polyfluoroalkyl substances comprising several millions of individual compounds of which around $10\,000^{10}$ are assumed to be currently in industrial use.¹⁵ PFAS are a concern because they persist in the environment and are toxic.^{10,11,16}

PFAS and other pollutants such as pharmaceuticals also are named “emerging pollutants”. However, this does not mean that these are new chemicals newly introduced into the environment or harmless because of the low concentrations, but rather that they were detectable only when suitable analytical methods became available. Often such chemicals were around in the environment without being noticed. The ever-increasing number of marketed chemicals and their presence in the environment is a huge challenge as new detection and clean-up methods have to be developed. Sophisticated instrumentation is needed to detect chemicals in the environment at very low levels, providing an early warning of potential harm to human health and the environment. Risk assessments need to consider both fate and

concentration of chemicals in the environment, along with knowledge of their effects on humans (toxicity) and organisms in the environment (eco-toxicity).

3.2.4 Pollution Prevention in Industry

As a reaction to the challenges and insights described earlier, industry started to develop and practice pollution prevention instead of mitigation only by end-of-pipe measures in the 1970s. These were supported by academic researchers beginning in the 1980s. In the 1990s, several organizations such as the U.S. Environmental Protection Agency (EPA), the Organisation for Economic Co-operation and Development (OECD), the European Union (EU), the Japan Chemical Innovation Institute (JCII), national chemical societies, and many individuals suggested several names, frameworks, and tools to address pollution prevention approaches and principles, including “simple chemistry”¹⁷ and “sustainable chemistry”.^{17,18} The International Union of Pure and Applied Chemistry (IUPAC) named it green chemistry for sustainability.^{18,19} The term “green chemistry” was introduced by the U.S. EPA in the 1990s.²⁰ The term “sustainable chemistry” originated from the Gesellschaft Deutscher Chemiker, *i.e.*, the German Chemical Society.²¹ The Rio Declaration within Agenda 21 (1991) stated that it is important for research to intensify the development of safe substitutes for chemicals with long life cycles (Agenda 21, #19.21).

The atom economy and the E-factor approaches were published in 1991 and 1992, respectively, giving tools to reduce waste within chemical synthesis.^{22,23} In 1996, the EC Council Directive (96/61/EC) presented a legal framework for integrated pollution prevention in chemical and adjacent industries, naming 12 considerations to be taken into account in determining the best available technologies.²⁴ The 12 Principles of Green Chemistry (published in 1998) reflect some of these considerations with principles for reducing energy use, reducing hazards and waste, and preventing pollution.²⁵

While these pollution prevention and hazard reduction approaches provide useful guidance to chemists, they do have drawbacks. For example, green chemistry Principle 7 calls for the use of renewable resources but does not address the pitfalls linked to renewable resources (biomass needs to be grown, space and water is needed, pesticides and fertilizers may be applied, chemicals need to be extracted, *etc.*). Using agricultural residues may impact soil fertility and local societies. Using a material of high polarity (biomass) for the synthesis of a chemical of low polarity requires many reactions, each of them needing energy, auxiliaries, and generating waste. Even though non-renewable, fossil fuels are probably the better starting material in some cases.²⁶

3.2.5 Chemistry’s Contribution to a More Circular Economy

The iceman “Oezi”, living more than 5000 years ago,²⁷ and other archeological findings teach us that humankind converted considerable amounts

of materials into useful products, such as birch wood into tar, which was used as a sealing agent for boats. They extracted dyes from plants and animals, used metal oxides as paints and in cosmetics, extracted the metals and metalloids in minerals and got metals such as iron, copper, and tin, and created materials new to nature, such as bronze, by mixing them. Extraction of metals from minerals takes effort; therefore, products were appreciated and used prudently and parsimoniously. Recycling by remelting these alloys, *i.e.*, products at the end of their life, of the same grade and composition was done in the copper and iron ages. Keeping products separate and sharing knowledge of their composition to enable high-quality recycling of products was practiced. Circulating and recycling was the norm in human history, not the linear flow-through economics of today.

Especially since the 1950s, with the full switch to fossil fuels as an energy resource and a rich source for organic chemicals, there has been a tremendous increase in the use of resources, related substances, materials, and product flows (“the great acceleration”).^{28,29} Not surprisingly, this resulted in increased environmental pollution from extraction and synthesis.

The concept of a circular economy relevant to chemistry was addressed in the 1970s based on concern about environmental pollution.³⁰ The basic principles of a circular economy were published in 1982.^{31,32} Twenty-five years later, the same concept was presented as “cradle-to-cradle” or “circular economy”. Recently, circular economy was introduced as a political strategy in Europe.^{33,34} Circular economy is an important concept to deal with the products of chemical and allied industries, yet it has clear and severe limitations.³⁵

The concept of circular chemistry, published in 2019, addresses the role of chemistry in enabling chemical products to be recyclable (Chapter 1 lists the 12 Principles of Circular Chemistry).³⁶ Several of these principles are similar to the 12 Principles of Green Chemistry, while others refer to newer concepts, such as the ladder of circularity and the need for a coherent policy framework. Like green chemistry, the concept of circular chemistry focuses on individual chemicals, materials, and products. It neglects the resulting local, regional, and global total flows of matter and energy and the broader concept of sustainability.

Authors of the 12 Principles of Circular Chemistry claim a waste-free industry if the principles are applied. This is not possible according to the three laws of thermodynamics. From a basic laws of nature perspective, *i.e.*, thermodynamics, there can only be down-cycling, as waste and losses, degradation, dissipative energy, *etc.* are unavoidable. Therefore, as energy is limited, and entropy would be endless, there is no upcycling from a thermodynamics perspective. Furthermore, with each recycling loop, the quality of the starting material and the resulting products are becoming worse. This often results in one cycle only, let alone “endless” recycling.

However, the term upcycling commonly refers to recycling of waste or products at the end of their life, *i.e.*, turning waste or used products of low economic value into products of higher economic value. This narrow view of

upcycling focuses on the increased economic value of some of the material only. It does not take a systems thinking point of view, which would include the generated waste, losses, entropy increase, and principal limitations set by thermodynamics. There can only be an economic re-valorization of a share of a waste material. Therefore, first and foremost we have to reduce substances, materials, and product flows from the very beginning to reduce entropic losses as best as possible.

Designing products for recycling is key.³⁷ In addition, it is also important to consider the lifetime of resources, processes, and products, as well as their usage along their full life cycle.^{38,39} One approach to minimizing waste and maximizing resource use is called the 3Rs: Reduce, Reuse, and Recycle. These 3Rs relate to a ladder of recycling: Reduce, which relates to the precautionary principle and beginning of pipe measures, followed by Reuse and Recycle. Applying this thinking results in a hierarchy of approaches when it comes to recycling itself:^{37,38}

1. Keep parts (“macroscopic” building blocks)
2. Keep form and size (*e.g.*, do not cut materials such as plastics, textiles, metal sheets and parts, and electronic material into pieces)
3. Keep material (*e.g.*, remold, recast thermoplastics, metals, alloys; avoid thermoset plastics)
4. Keep composition (*e.g.*, do not add or remove constituents such as additives or other components when reprocessing)
5. Keep molecules (*e.g.*, solvolysis of polymers instead of depolymerization; solvolysis can be used to remove unwanted legacy chemicals)
6. Keep molecular building blocks (*e.g.*, monomers from depolymerization)
7. Keep atoms (*e.g.*, pyrolysis of plastics, separation of metals in metal recycling and avoid transfer of metals into slag; can be used to remove toxic elements)
8. Keep energy (so called “thermal” recycling of organic materials, which is in fact incineration only, resulting in ultimate destruction of materials)

Nature is very successful in reusing its materials. However, nature’s loops are very different from those in the technosphere. For example, only a few chemical elements are used in higher amounts (*e.g.*, carbon, hydrogen, oxygen, nitrogen, some sulfur and phosphorous). Furthermore, nature employs just a few building blocks, such as glucose (cellulose, starch, and derivatives such as chitin), a limited number of amino acids (proteins), fatty acids, isoprenoids, and phenols (lignin, flavonoids). Interestingly, toxic materials, such as heavy metals or the halogens, are not easily (if at all) accessible to living organisms. In nature, most metals are immobilized in the form of minerals.

Nature’s cycles most often are local ones, especially those related to biomass, such as leaves, straw, husks, wood, insects, and animal carcasses. In contrast to the modern economy, nature reuses (“recycles”) its building blocks on a small spatial scale, *e.g.*, at the place where organisms grow, live,

and die. Furthermore, the products of nature and the related mass flows do not significantly change within decades, allowing living organisms to adapt (evolve) over longer time scales to use the materials as food and building blocks. This is in stark contrast to regional or even global anthropogenic cycles of elements, synthetic molecules, metals, materials, and products, both in qualitative and quantitative aspects.

3.2.6 Chemistry Within/For Sustainability

Sustainable development means ensuring that the needs of the present are met without compromising the ability of future generations to meet their own needs.⁴⁰ This encompasses all three sustainability strategies, *i.e.*, efficiency, consistency, and sufficiency.⁴¹ Efficiency in the context of sustainability means to use fewer materials and less energy to get the same quantity of products. Consistency aims to achieve better compatibility with nature. Sufficiency addresses consumption in contrast to efficiency and consistency, which focuses on the production side of goods. Sufficiency aims to reduce (over)consumption and to reduce the environmental burden of consumption. A growing body of scientific evidence suggests that sustainability goals cannot be achieved through technological innovations alone. Social aspects (not just the economy), ethics, and all stakeholders along the life cycle of products need to be included, too.

The precautionary principle is one of the basic principles of all societies in human history and everyday human behavior. The precautionary principle creates awareness of the limits of our knowledge and possible actions. The precautionary principle means taking action even if there is not (yet) a clear cause-and-effect relationship established, but good evidence for it.^{42,43} It is the basis of all policies of the European Union.⁴³

Recently, it was stated that manufactured chemicals have transgressed their planetary boundary.⁴⁴ As we cannot really know the planetary boundaries for chemicals, we need a precautionary attitude. The Sustainable Development Goals (SDGs) were adopted by all United Nations Member States as overarching goals to support sustainable development. To meet the SDGs and stay within the planetary boundaries, chemistry has a pivotal role.⁴⁵ The Safe and Sustainable by Design (SSbD) framework of the EU includes hazard, safety, environmental, and social assessment at the design phase of new chemical products as a precautionary approach.⁴⁶

The term sustainable chemistry was introduced in the 1990s. Although the terms green chemistry and sustainable chemistry are different, sometimes they have been used synonymously. Nearly all definitions of sustainable chemistry do not refer to the three strategies of sustainability (sufficiency, efficiency, consistency). This, however, is mandatory to enable chemistry to contribute in a sustainable manner to sustainability. Sustainable chemistry lays out overarching characteristics that describe how chemistry has to be embedded into sustainability (Box 3.1).⁴⁷ It is based on systems thinking.⁴⁸ As such, sustainable chemistry goes beyond the 12 Principles of Green

Box 3.1 Key Characteristics of Sustainable Chemistry.

1. **HOLISTIC:** Guiding the chemical science and the chemical sector towards contributing to sustainability in agreement with sustainability principles and general understanding and appreciating potential interdependencies including long-distance interactions and temporal gaps between the chemical and other sectors.
2. **PRECAUTIONARY:** Avoiding transfer of problems and costs into other domains, spheres and regions at the outset, preventing future legacies and taking care of the legacies of the past including linked responsibilities.
3. **SYSTEMS THINKING:** Securing its interdisciplinary, multi-disciplinary and transdisciplinary character including a strong disciplinary basis but taking into account other fields to meet sustainability to its full extent. Application as for industrial practice including strategic and business planning, education, risk assessment and others including the social and economical spheres by all stakeholders.
4. **ETHICAL AND SOCIAL RESPONSIBILITY:** Adhering value to all inhabitants of planet earth, human rights, and welfare of all life, justice, the interest of vulnerable groups and promoting fair, inclusive, critical, and emancipatory approaches in all its fields including education, science, and technology.
5. **COLLABORATION AND TRANSPARENCY:** Fostering exchange, collaboration, and right to know of all stakeholders for improving the sustainability of business models, services, processes and products and linked decisions including ecological, social, and economic development on all levels. Avoiding all “green washing” and “sustainability washing” by full transparency in all scientific and business activities towards all stakeholders, and civil society.
6. **SUSTAINABLE AND RESPONSIBLE INNOVATION:** Transforming fully the chemical and allied industries from the molecular to the macroscopic levels of products, processes, functions, and services in a proactive perspective towards sustainability including continuous trustworthy, transparent, and traceable monitoring.
7. **SOUND CHEMICALS MANAGEMENT:** Supporting the sound management of chemicals and waste throughout their whole life cycle avoiding toxicity, persistency and bio-accumulation and other harm of chemical substances, materials, processes, products and services to humans and the environment.
8. **CIRCULARITY:** Accounting for the opportunities and limitations of a circular economy including reducing total substance flows, material flows, product flows, and connected energy flows at all spatial and temporal scales and dimensions especially with respect to volume and complexity.

9. GREEN CHEMISTRY: Meeting under sustainable chemistry applications as many as possible of the 12 Principles of Green Chemistry with hazard reduction at its core when chemicals are needed to deliver a service or function whenever and wherever this complies with sustainability.
10. LIFE CYCLE: Application of the above-mentioned key characteristics for the whole lifecycle of products, processes, functions, and services on all levels, *e.g.*, from molecular to the macroscopic levels and all sectors in a pro-active perspective towards sustainability.

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Chemistry and Circular Chemistry. Sustainable chemistry is also based on the precautionary principle, fairness and transparency, and enables chemistry to operate within the planetary boundaries and to contribute to all the SDGs in a sustainable manner.

Accordingly, sustainable chemistry starts by asking the question “Do we need a chemical product for a certain service and function or is a non-chemical, non-material based option available?” *i.e.*, taking into account non-material based alternative behaviors and business models.⁴⁵ This is counterintuitive for chemists and the chemical sector, as their inherent goal as the science and industry of the transformation of matter is to come up with ever new chemicals and products. Thus, sustainable chemistry strives for the highest standards everywhere, including where and how resources are extracted, used, and recycled, ethics, and what the environmental, social, and economic impact on local societies is.

Sustainable chemistry acknowledges that planet earth is the basis of it all. Accordingly, chemists and related professionals need to draw insights from multiple scientific disciplines and engage in extensive collaborations. Such changes will require the transformation of current education models, re- and up-skilling the workforce. Sustainability-oriented learning networks that accumulate knowledge on specific topics such as policy, education, business, and entrepreneurship will need to be fostered, supporting thinking in a holistic sustainable manner while ensuring the exchange of the best and latest research regarding impact on sustainability.

3.2.7 Interrelationships

The ever-increasing extraction of resources, product flows, and the generation of waste and environmental pollution are in strong contrast to sustainability. Sustainable chemistry is the framework for chemistry to minimize these in a sustainable manner. Accordingly, sustainable chemistry acknowledges green chemistry and circular chemistry as important tools in the synthesis and recycling of chemicals and related products, but it encompasses much more. Table 3.1 summarizes the main characteristics and limitations of environmental, green, circular, and sustainable chemistry.

Table 3.1 A summary of the characteristics of green chemistry, circular chemistry, and sustainable chemistry.

Approach	Time	Main characteristics	Main limitations
Environmental chemistry	1970s–now	Analyzing the presence and fate (<i>e.g.</i> , degradation, (bio)accumulation) of chemicals in the environment including organisms, effects on the environment (<i>e.g.</i> , the ozone layer)	Informs, but does not prevent by itself further environmental impact
Green chemistry	The term green chemistry was introduced in the early 1990s; EU directive in force in 1996; 12 Principles of Green Chemistry published in 1998	Principles to reduce waste, energy, and hazards in synthesis and chemicals; use of renewable resources and less hazardous chemicals; focused on pollution prevention	Focused mainly on individual chemicals and synthesis rather than material and product flows, service and function
Circular chemistry	Published in 2019	Addresses the role of chemistry and the design of products and processes to allow for and support a circular economy	Focus on re-cycling only, on individual products; states a zero-waste industry which is not possible according to the laws of thermodynamics
Sustainable chemistry	Term first used in 1990s by German Chemical Society, EU, IUPAC and OECD (understanding close to green chemistry), full elaboration 2003–2021	Characterized by systems thinking and starting with service and function needed, taking into account nonmaterial services and overarching issues such as ethics, fairness and transparency; aims to reduce total substance, material, and product flows	Is a challenge for conventional chemistry as the goal of industry is to transform materials and come up with ever new products instead of aiming to reduce them

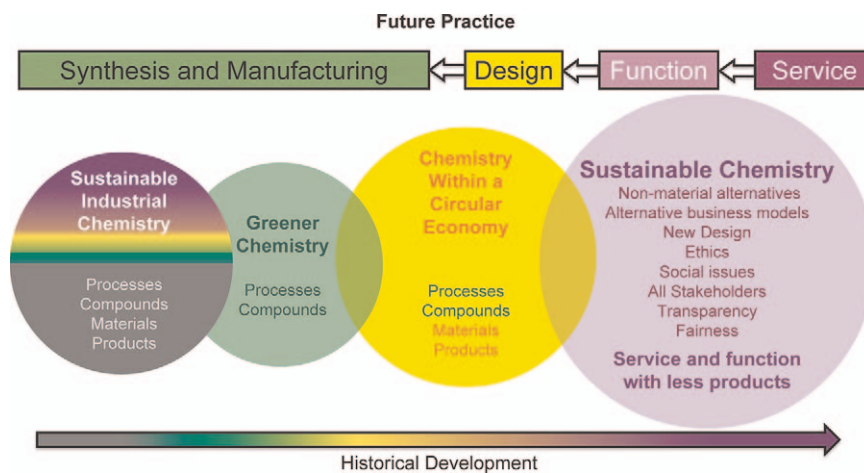


Figure 3.2 Historical development of practicing chemistry (lower half) and future practicing of chemistry (upper half).

While the historical development of chemistry as an industrial sector is from left to right in the lower half of Figure 3.2, its future practice needs to be from right to left, as shown in the upper half of the image. Sustainable chemistry starts by asking what is the needed service and function, and considers ethics, social issues, *etc.* If a chemical is required to deliver the service needed, it will be designed to fit into a circular economy. If it cannot be circulated and will end up in the physical environment, it will be designed for fast and full environmental mineralization. After these modifications have been made, chemicals will be synthesized according to the principles of green chemistry, meeting as many as possible. This is all part of the sustainable chemical industry of the future.

3.3 Teaching & Learning a Sustainability Topic

Using the topic of PFAS, this section offers information for instructors that should help students learn to connect conventional chemistry, green chemistry, circular chemistry, and sustainable chemistry.

3.3.1 A Basic Understanding of PFAS

3.3.1.1 PFAS Chemistry

Now practically a household term, PFAS (pronounced P-fas) stands for perfluoroalkyl and polyfluoroalkyl substances. People also refer to these substances as “forever chemicals”. Given the ability of PFAS to withstand

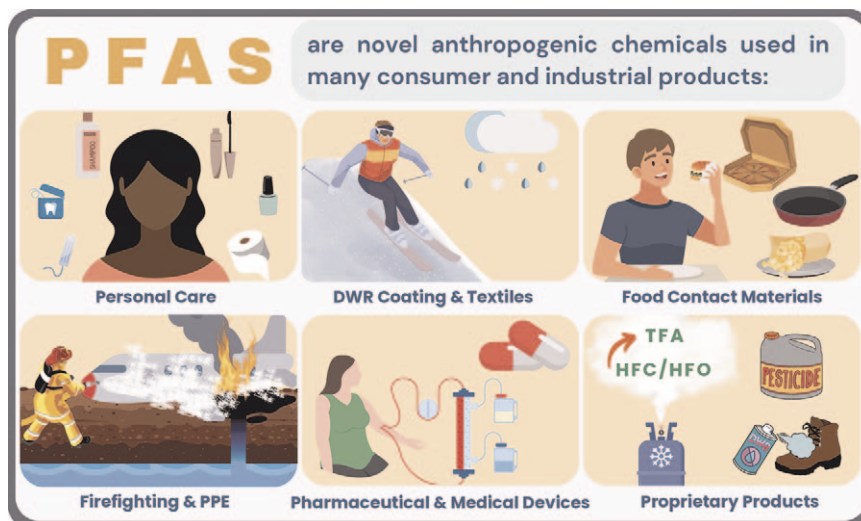


Figure 3.3 Examples of products containing PFAS. Courtesy of Ayra Nacilla.

degradation in the environment, these substances persist today and are present in drinking water, in soils, in foods, and even in our bodies.

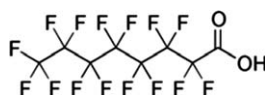
PFAS were produced on a large scale in the 1940s and 1950s and found uses widely in industry, in the military, and in consumer products. The infographic in Figure 3.3 depicts a sample of these uses. Notably, PFAS have been found in many other products, such as electronics and pharmaceuticals, and as additives and auxiliaries (*e.g.*, lubricants) to support processing. As contaminants in low concentration in a product, PFAS also may be released during their use into the environment.

Public reports and infographics such as the one shown in Figure 3.3 tend *not* to include either chemical names or chemical formulas. But as a chemistry instructor, your approach to PFAS is likely to be more rigorous. To help your students learn what happened when PFAS became omnipresent in our world, most likely you will want to combine chemistry knowledge with the perspectives gained from the recent history of PFAS. As a starting point, Box 3.2 contains some basic chemical knowledge; an internet search can quickly provide additional information about PFAS. For example, here is a more detailed definition of per- and polyfluoroalkyl substances:

“Fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it), *i.e.*, with a few noted exceptions, any chemical with at least a perfluorinated methyl group ($-\text{CF}_3$) or a perfluorinated methylene group ($-\text{CF}_2-$) is a PFAS”. The “noted exceptions” refer to a carbon atom with a H/Cl/Br/I atom attached to it.⁴⁹

Box 3.2 A summary of basic PFAS chemistry.

- Per- and polyfluoroalkyl substances (PFAS) are organofluorine compounds that do not occur naturally.
- In polyfluoro compounds, some of the H atoms on the alkyl chains are replaced by F atoms; in perfluoro compounds, all H atoms on the chains are replaced.
- Due to different chain lengths, substitution patterns, and functional groups on the alkyl chain, millions of PFAS have been synthesized.
- Perfluorooctanoic acid (PFOA) is an example of a PFAS.



Note that the alkyl chain in PFOA has many possible isomers. These isomers may form as unwanted by-products and are often not removed from the resulting mixture for reasons of cost.

- The properties of a particular PFAS depend on chemical structure. For example, PFOA has a polar “head” (the carboxylic acid) and a nonpolar “tail”, the perfluoro alkyl chain. With this dual solubility, it functions as a surfactant. With many fluorine atoms, it is water repellent at the same time. PFOA was banned in 2020 in the EU and in 2021 in Switzerland.
- PFAS tend to be stable to heat and to chemical degradation. They were nicknamed “forever chemicals” because of their long persistence in the environment.

3.3.1.2 PFAS: The Wider Context

This section examines perspectives on PFAS that one can gain through examining the bigger picture and describes several points that connect to the history of PFAS and its wider context.

1. **Availability of Data:** it is reported that more than 300 000 chemicals are marketed globally.⁵⁰ Given this large number, data on each chemical’s environmental fate and health effects are limited.⁵¹ Around 10 000 PFAS are in use. PFAS have contaminated the environment, including drinking water and food. Similarly, data on PFAS are limited, as is displayed in Figure 3.4.⁵² It is known, however, that PFAS are toxic to humans.^{10–12,15,16,53,54}

As each new compound emerges, its environmental fate needs to be assessed, a time-consuming process. Sustainable chemistry and precautionary approaches would do this early in the development of a new compound, not close to its application for authorization. Because of the high number of PFAS and their chemical similarity, the

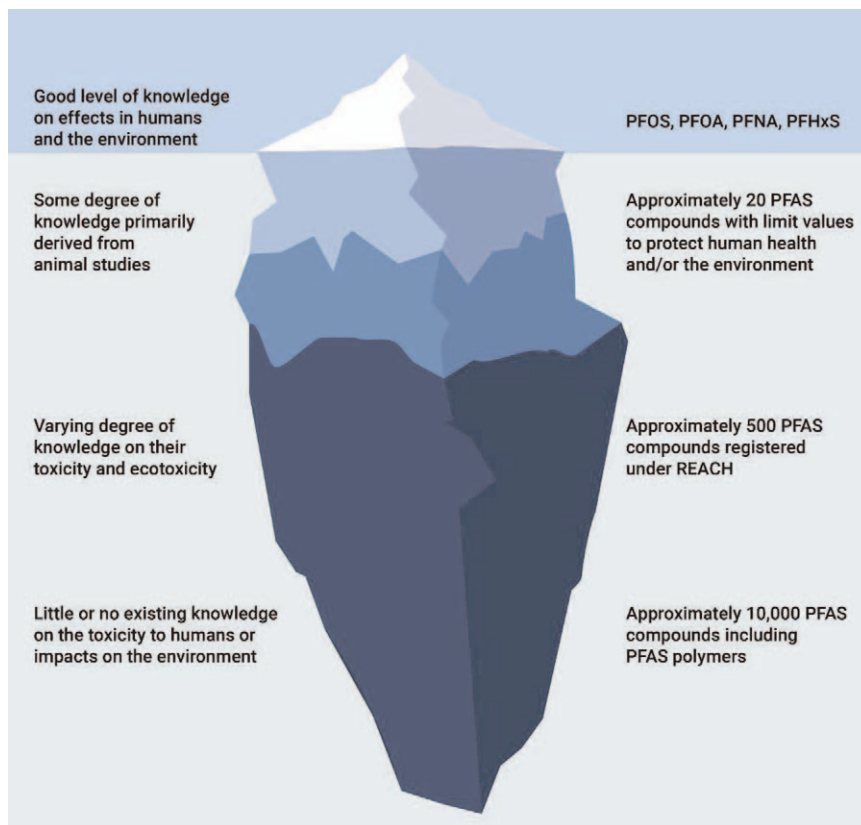


Figure 3.4 Level of knowledge of human health and environmental impacts of PFAS. Reproduced from ref. 51 with permission from European Environment Agency.

conventional compound-by-compound assessment will not solve the issue.¹⁶ Accordingly, the European Union has proposed a group-based risk assessment within its Chemicals Strategy for Sustainability (CSS).⁵⁵ This saves time, lowers costs, and prevents the substitution of a similar chemical not yet banned but could be expected to have similar properties. PFAS are but one of the latest examples of compounds needing assessment. Some PFAS are listed by the Stockholm Convention as persistent organic pollutants (POPs).

2. **Multitude of Types & Uses:** over the years, more than 10 000 PFAS have been put into use, and several million more are known. These substances have found uses in many processes and products because of their chemical stability, their physical-chemical properties, and their resistance to degradation. Uses of PFAS include surfactants and water and grease repellents, such as additives to produce textiles (especially for outdoor wear), ski waxes, stain-resistant fabrics, and firefighting

foams. PFAS are used in many industrial sectors. In the energy sector, PFAS are used in products needed to generate renewable energy such as solar collectors and photovoltaic cells; batteries (such as lithium-ion, vanadium redox, and zinc); coatings for the blades of windmills; and carbon capture and green hydrogen generating processes. It is known, however, that there are alternative processes that do not rely on PFAS.

3. **Public Awareness:** only recently have PFAS been in the public eye. Their notice was triggered by increased availability of more sophisticated analytical methods such as better separating columns in combination with high-resolution mass spectrometry. The attention received by PFAS follows a well-known pattern: with new analytical methods, new pollutants can be detected. For example, polychlorinated biphenyls (PCBs) first were detected in environmental samples in 1969 when gas chromatography became available.⁵⁶
4. **Public health:** because of their persistence and their physical-chemical properties, PFAS are mobile in the environment and can be found everywhere. They accumulate in wildlife and in humans. Studies have identified a link between exposure to PFAS and adverse health impacts, including breast cancer, liver, and kidney disease. They are also classified as endocrine-disrupting chemicals.^{53,57-59}
5. **Dealing with the consequences:** clean-up is challenging, if not impossible, for several reasons, including that PFAS are ubiquitous. In addition, it is costly both to let PFAS remain in the environment and to monitor or to remove these substances. For example, the annual health-related costs for PFAS were estimated at 52–84 billion euros in the European Economic Area⁵³ and at 60 billion dollars in the USA.⁵⁴ Costs for environmental monitoring are estimated at up to € 170 billion. The US Water Works Association estimates the price tag to remove PFAS from drinking water to be about \$ 370 billion.⁶⁰ In 2023, the average market price for PFAS was estimated to be 19 € kg⁻¹. However, when societal costs are included, this estimate rises to 18 700 € kg⁻¹.⁶¹

3.3.1.3 PFAS Connections to Sustainable Chemistry

Green chemistry, circular chemistry, and sustainable chemistry have all emerged in the past few decades. Teaching and learning about PFAS can highlight how these three orientations toward sustainability achieve different but compatible goals.

We begin first with PFAS and the 12 Principles of Green Chemistry listed earlier in Chapter 1 (Box 1.1). As was pointed out, green chemistry is the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances. The 12 Principles can be applied to a particular synthesis, how it is carried out, the individual products, and reducing their hazards and presence in the environment.

At the time that PFAS were first manufactured, the Principles of Green Chemistry had not yet been articulated; more generally, pollution prevention

was not yet fully developed. The manufacture of PFAS did not align with at least these two Principles of Green Chemistry:

- #3. Wherever practicable, synthetic methodologies should be designed to use and generate substances that possess little or no toxicity to human health and the environment.
- #10. Chemical products should be designed so that at the end of their function they do not persist in the environment and break down into innocuous degradation products.

The 12 Principles of Circular Chemistry, listed in Chapter 1 (Box 1.3), also are relevant to the study of PFAS. As pointed out earlier, for a circular economy, the atoms, molecules, and materials in products are circulated; at the end of the product's life, these atoms and molecules repeatedly are recycled within the economy. Again, the Principles of Circular Chemistry were articulated after the first large-scale production of PFAS. Even so, Principles of Circular Chemistry were and still are directly relevant to the recent history of PFAS in the environment. For example, the harm to human health and the environment caused by PFAS is not consistent with Principle #6: No out-of-plant toxicity. Chemical processes should not release any toxic compounds into the environment.

Lastly and most important to this chapter, consider sustainable chemistry. Chapter 1 referred to the OECD definition: "Sustainable chemistry encompasses the design, manufacture, and use of efficient, effective, safe, and more environmentally benign chemical products and processes". Sustainable chemistry, however, encompasses much more than just a particular chemical reaction or product and asks questions concerning wider parameters (*e.g.*, energy, materials, economics, social aspects, fairness and transparency, non-material and other alternative business models, and ethics (Box 3.1)) about the sustainability of the entire system. Had such thinking been applied, including the precautionary principle, most likely the PFAS case could have been avoided. As such, sustainable chemistry provides an overarching set of goals for chemists, inclusive of both green chemistry and circular chemistry.

Clearly, sustainable chemistry speaks to the entire life cycle, not just the value chain. People failed to address the tenets of sustainable chemistry before manufacturing PFAS. Some important questions were not asked and answered, and a sample of these questions, mapped to the characteristics of sustainable chemistry, is listed in Table 3.2.

3.3.2 PFAS Connections with the Chemistry Curriculum

The chemistry of PFAS (together with the broader societal issues to which it connects) could find a home in multiple courses in an undergraduate chemistry curriculum. Table 3.3 lists some of the possibilities. Ideally, information about PFAS would be carefully scaffolded, introducing the

Table 3.2 The connections between PFAS and the characteristics of sustainable chemistry.

Characteristics of sustainable chemistry	Sustainable chemistry would have asked questions such as these prior to the manufacture of PFAS
Holistic	Which service should be delivered by a PFAS? Is this new PFAS essential to our health and our wellbeing?
Precautionary	What is the current state of our knowledge of PFAS, and which gaps exist in this knowledge? Are PFAS toxic to humans and other species? What is the fate of PFAS in the environment? Are PFAS expected to bioaccumulate? What unintended consequences should be anticipated and how could they be managed?
Systems thinking	To which parts of the wider system do PFAS connect? How could PFAS be removed from parts of the system, such as drinking water or soil? How could technical, legislative, and/or political means prevent PFAS from moving throughout the system? What are the relevant time scales? Are there windows of opportunity in which to take action if needed?
Ethical & social responsibility	Who will be the winners and losers in manufacturing PFAS? How will the manufacture of PFAS impact vulnerable groups now and in the future? Who will generate data on properties (<i>e.g.</i> , hazard, fate), scale of production, and profit? How will the data be shared and its quality and accessibility be safeguarded? Who will pay for measures needed to prevent the loss of health and adverse environmental impacts?
Collaboration & transparency Sustainable & responsible innovation	Have communities been consulted before using PFAS? Which stakeholders should be engaged? Is this new PFAS really needed? Would a different compound be likely to work just as well? Should we consider not producing this PFAS at all?
Sound chemicals management	How are chemicals used in the manufacture of PFAS sourced? What are the hazards and risks of these chemicals? How will stocks of PFAS be cared for? Who will do this and pay for it?
Circularity	What happens to PFAS after their intended use? Can PFAS be designed to be part of the circular economy?
Green chemistry	Are the starting materials, reagents, and solvents used in the manufacture of PFAS hazardous? Can new PFAS be designed by applying the principles of green chemistry?
Life cycle	Has a Life Cycle Analysis (LCA) been completed? Which steps in the life cycle and properties of PFAS can be improved to make the processes and PFAS more sustainable?

Table 3.3 Chemistry topics that connect to PFAS. The ones listed here could be placed in several different courses.

Course	Chemistry topics
Foundational chemistry	Solubility Volatility Bond strengths Constitutional isomerism Halogens Green chemistry, circular chemistry Sustainable chemistry
Organic chemistry	Alkyl groups Fluorine chemistry Fluorocarbons and other halogenated organic chemicals (<i>e.g.</i> some of the legacy chemicals such as CFCs, Seveso Dioxin, polychlorinated biphenyls, brominated flame retardants; why iodinated organics are not persistent) Persistent organic pollutants (POPs)
Analytical chemistry	Water, air, and soil analysis Analysis of chemicals in human body fluids Methods of PFAS detection and measurement
Industrial chemistry	Surfactants Water repellents Lubricants
Biochemistry	Toxicology Eco-toxicology
Inorganic chemistry	Fluorine chemistry Where and how to source fluorine
Environmental chemistry	Detecting pollutants <i>vs.</i> preventing pollution Environmental persistence and accumulation Environmental risk assessment of chemicals

substances and related aspects to pollution prevention, green, circular, and sustainable chemistry early in a foundational chemistry course so as to be able to build on the concepts in later courses.

Instructors of entry-level courses, however, are likely to be aware that many of their students will take no further courses in chemistry. Thus, these instructors might choose to give enough PFAS coverage in their foundational course to ensure that PFAS would be on the radar screen of their students in the years to come. An important learning outcome, highlighted in the next section, is for students to know that many stories about substances like PFAS have taken place in the past while others are yet to be written.

3.3.2.1 Sample Student Learning Outcomes

Any student learning outcomes written for the topic of PFAS need both to be in harmony with the overall goals of a course and to be complementary to those for related topics. Accordingly, this section offers a set of possible learning outcomes that instructors may want to adapt for their own purposes. In addition, as noted in the previous section, new issues for PFAS are

likely to emerge over time. Thus, an openness to new insights, new developments, and possibly even to new hazards should underlie the process of teaching and learning about PFAS.

The first set of learning outcomes (Box 3.3) are listed for a foundational chemistry course. These also could be appropriate for students in an environmental, toxicology, biochemistry, or sustainability science course. Those listed next are for higher-level chemistry courses. Unlike the ones listed for foundational courses, these learning outcomes probe the differences between

Box 3.3 Sample learning outcomes for PFAS in different chemistry courses.

Foundational Chemistry Courses

Students should be able to:

- Explain the name PFAS. Give an example of this class of substances.
- Explain why PFAS are called “forever chemicals”.

More generally, students should be able to:

- List the desirable properties of PFAS that led to their manufacture and use.
- List several uses of PFAS.
- List the undesirable properties of PFAS.
- List the relationship of these to unwanted effects within humans and the environment.
- Summarize (for a non-technical audience) an article on the environmental fate of PFAS.
- Summarize (for a non-technical audience) an article on the health consequences of PFAS in humans.

For green chemistry, circular chemistry, and sustainable chemistry, students should be able to:

- Provide a description of each suitable for the general public.
- Explain some of the principles of green chemistry and circular chemistry and the key characteristics of sustainable chemistry.

More Advanced Chemistry Courses

For green chemistry, for circular chemistry, and for sustainable chemistry, students should be able to:

- Provide a description of each suitable for chemistry professionals.
- Compare and contrast the principles of green and circular chemistry.
- Critique the shortcomings of each with respect to sustainability, as well as the merits of each with respect to sustainability.
- Apply each one to the design, production, and use of PFAS.
- Describe the characteristics of sustainable chemistry that differ from green and circular chemistry.

For PFAS, students should be able to:

- Describe an alternative to a current use of PFAS.
- Suggest an area for which more information is needed to assess the impact of PFAS.

Chemistry Courses with a Broader Scope

Students should be able to:

- List both positive and negative ways in which humans and human activities have been impacted by PFAS.
- Research a current sustainability-related issue related to PFAS, preferably in your own community. Present your findings.
- Propose a sustainability-related action related to PFAS that your community could take. Analyze its feasibility.

green chemistry, circular chemistry, and sustainable chemistry in more detail. As such, they require higher level knowledge and thinking skills. The learning outcomes for upper-level chemistry courses could also be useful in chemical engineering or industrial chemistry courses. Finally, the last set of learning outcomes are broader in scope and may be useful to instructors at any level who want to offer students the opportunity to investigate sustainability issues more fully, especially ones in their own communities.

Although these learning outcomes are written for the topic of PFAS, they could also be more widely applicable to other current topics such as refrigerant gases (see Chapter 8), plastics (see Chapter 7), polymer additives, lubricants, pesticides, personal care products, pharmaceuticals, batteries, photovoltaic cells, wind turbines, and construction materials.

3.3.3 Activities, Pedagogies, and Real-world Examples

This section offers three sets of student activities that relate to PFAS (Box 3.4):

Activity Set #1 focuses on PFAS and their properties.

Activity Set #2 takes a wider view and offers students opportunities to learn more about a PFAS of their choice.

Activity Set #3 connects the dots back to sustainability, having students compare and contrast green chemistry, circular chemistry, and sustainable chemistry.

Rather than addressing multiple issues more broadly, instructors may choose to delve more deeply into just one of the uses of PFAS. We suggest additional topics such as the use of PFAS in ski waxes, textiles, gaskets, electronics, batteries, or greener hydrogen production. Such topics could be worked on later by more advanced students. Instructors who choose to pursue a specific use may wish to build an activity set of their own.

Box 3.4 Three sets of student activities for the topic of PFAS.

Activity Set #1

PFAS and their Properties

1. Tell the story of a PFAS. First, give its name and structural formula. Next, describe the properties that you would expect this substance to have. Also, describe the use of this substance, either in industry, in the military, or in the home. Finally, form a small group and compare notes on the PFAS that each group member selected.
2. Create a timeline for dates important in the past and current history of PFAS, from the 1940s to the present.
3. Here are several PFAS that were widely produced:

Abbreviation	Chemical name
PFOS	Perfluorooctane sulfonic acid
PFOA (aka C8)	Perfluorooctanoic acid
PFNA	Perfluorononanoic acid
PFDA	Perfluorodecanoic acid
PFOSA (FOSA)	Perfluorooctane sulfonamide

Select one of the PFAS and describe its uses and eventual fate in the environment. Form a small group and compare notes.

Activity Set #2

Issues that connect to PFAS

1. How do humans get exposed to PFAS? Outline at least three sources and pathways.
2. From the list of PFAS in Activity Set #1, select one and research what is known about its toxicity to humans and/or to organisms in the wider environment.
3. The infographic in Figure 3.2 shows six uses for PFAS. Research one of these to learn the issues involved. Then join others who made the same choice and report your findings to the whole class.
4. PFAS have found many uses other than those shown in Figure 3.2. Research another use and the issues involved. Report your findings to the whole class. Compare what you have learned with others, as for #3.
5. Which compounds today are replacing PFAS? Cite some examples. Can any of the issues related to PFAS be expected for them too? Why or why not?

Activity Set #3**Green Chemistry, Circular Chemistry, and Sustainable Chemistry**

1. For green chemistry, circular chemistry, and sustainable chemistry
 - a. Describe each one in general terms for a lay audience.
 - b. Describe each one for a technical audience.
 - c. Create a figure that shows the relationships among all three.
2. Pick one the characteristics of sustainable chemistry (Box 3.1). How might the story of PFAS in the environment have turned out, had this characteristic been heeded?
3. Examine your response to the previous question. Is it unique to PFAS or does it apply more broadly to other chemicals?
4. Critique this line of reasoning. Cite examples from PFAS to make your case.

“Green chemistry has clear inherent limitations. The 12 Principles do not consider the basic principles of sustainability; rather, they focus on individual products of a synthesis. Products synthesized according to them are not necessarily greener or even more sustainable”.

3.4 Closing Thoughts

Chemistry and its industrial products contribute to our modern societies, including our standard of living, health, and food production necessary for a growing global population. Even without the knowledge of chemical principles that we possess today, chemistry was used early in human history. Later, accompanying the successes of industrial chemistry, the downsides of chemical products emerged.

A knowledge of chemistry in the context of sustainability will be fundamental as we journey together on the path to a more sustainable future. However, to accomplish our goals, we all need a broader understanding of chemistry than simply how to synthesize a chemical. Rather, we need to teach chemistry, and our students need to learn chemistry, in a much broader context. Sustainable chemistry offers this context and thus provides a path forward for students and their instructors alike.

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References

1. Wikipedia, https://en.wikipedia.org/wiki/Global_Industry_Classification_Standard (accessed August 2025).

2. R. Carson, *Silent Spring*, Fawcett Crest, New York, 1962.
3. K. Polanyi, *The Great Transformation: The Political and Economic Origins of Our Time*, Farrar & Rinehart, New York, 1944.
4. O. Melsted and I. Pallua, *Can. J. Hist.*, 2018, **53**, 395.
5. Technical University of Dresden, <https://de.wikipedia.org/wiki/Teerfarben#>, Collection of first useful tar dyes at Technical University of Dresden (accessed August 2025).
6. A. D. Ngo, R. Taylor, C. L. Roberts and T. V. Nguyen, *Int. J. Epidemiol.*, 2006, **35**, 1220.
7. WHO Regional Office for Europe, *Human biomonitoring: facts and figures*, <https://iris.who.int/handle/10665/164588> (accessed August 2025).
8. D. Briggs, *Br. Med. Bull.*, 2003, **6**, 11.
9. E. L. Schymanski, J. Zhang, P. A. Thiessen, P. Chirsir, T. Kondic and E. E. Bolton, *Environ. Sci. Technol.*, 2023, **57**, 16918.
10. European Chemicals Agency (ECHA), <https://echa.europa.eu/de/-/echa-publishes-pfas-restriction-proposal> (accessed August 2025).
11. United States Environmental Protection Agency (EPA), <https://www.epa.gov/pfas/pfas-explained>, (accessed August 2025).
12. I. T. Cousins, R. Vestergren, Z. Wang, M. Scheringer and M. S. McLachlan, *Environ. Int.*, 2016, **94**, 331.
13. P. Harremoës, D. Gee, M. MacGarvin, A. Stirling, J. Keys, B. Wynne and S. G. Vaz (eds.), *Late Lessons from Early Warnings: The Precautionary Principle 1896–2000*, European Environmental Agency, Copenhagen, 2001.
14. D. Gee, P. Grandjean, S. Foss Hansen, S. van den Hove, M. MacGarvin, J. Martin, G. Nielsen, D. Quist and D. Stanners (eds.), *Late Lessons from Early Warnings: Science, Precaution, Innovation*, European Environmental Agency, Copenhagen, 2013.
15. J. Glüge, M. Scheringer, I. T. Cousins, J. C. DeWitt, G. Goldenman, D. Herzke, R. Lohmann, C. A. Ng, X. Trier and Z. Wang, *Environ. Sci.: Processes Impacts*, 2020, **22**, 2345.
16. I. T. Cousins, J. C. DeWitt, J. Glüge, G. Goldenman, D. Herzke, R. Lohmann, C. A. Ng, M. Scheringer and Z. Wang, *Environ. Sci.: Processes Impacts*, 2020, **22**, 2307.
17. A. Kanai, in *Proceedings of the OECD workshop on sustainable chemistry Part I*, Paris, OECD, 1999, p. 72.
18. *Proceedings of the OECD workshop on sustainable chemistry Part I*, Paris, OECD, 1999, p. 72.
19. International Union of Pure and Applied Chemistry (IUPAC), <https://iupac.org/who-we-are/committees/sustainable-chemistry/> (accessed August 2025).
20. M. A. Murphy, *Found. Chem.*, 2018, **20**, 121.
21. M. Krasnodębski, *Found. Chem.*, 2023, **25**, 463.
22. B. M. Trost, *Science*, 1991, **254**, 1471.
23. R. A. Sheldon, *Green Chem.*, 2017, **19**, 18.
24. European Union (EU), <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A31996L0061> (accessed August 2025).

25. P. T. Anastas and J. C. Warner, *Green Chemistry. Theory and Practice*, Oxford University Press, Oxford, 1998.
26. J. Huo, Z. Wang, P. Lauri, J. D. Medrano-García, G. Guillén-Gosálbez and S. Hellweg, *Environ. Sci. Technol.*, 2024, **58**, 13748.
27. Wikipedia, https://en.wikipedia.org/wiki/%C3%96tzi#cite_note-Axe_South_Tyrol_Museum-56 (accessed August 2025).
28. W. Steffen, W. Broadgate, L. Deutsch, O. Gaffney and C. Ludwig, *Anthropocene Rev.*, 2015, **2**, 81.
29. E. Elhacham, L. Ben-Uri, J. Grozovski, Y. M. Bar-On and R. Milo, *Nature*, 2020, **588**, 442.
30. B. Commoner, *The Closing Circle: Nature, Man, and Technology*, Alfred A. Knopf, New York, 1971.
31. W. R. Stahel, in *An Inquiry into the Nature of Sustainable Societies: The Role of the Private Sector*, ed. S. G. Orr, Houston Area Research Center, 1982, pp. 74–96.
32. W. R. Stahel, *Nature*, 2016, **531**, 435.
33. European Commission (EC), https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en (accessed August 2025).
34. M. Yang, B. Huang, X. Xu, J. Zhou, W. McDowall, P. Andrews-Speed, Z. Liu and G. Yong, *Resour., Conserv. Recycl.*, 2022, **183**, 106350.
35. *The Impossibilities of the Circular Economy*, ed. H. Lehmann, C. Hinske, V. de Margerie and A. Slaveikova Nikolova, Routledge, London, 2023.
36. T. Keijer, V. Bakker and J. C. Sloopweg, *Nat. Chem.*, 2019, **11**, 190.
37. K. Kümmerer, J. H. Clark and V. G. Zuin, *Science*, 2020, **367**, 369.
38. V. G. Zuin and K. Kümmerer, *Nat. Rev. Mater.*, 2022, **7**, 76.
39. K. Kümmerer, *Time Soc.*, 1996, **5**, 209.
40. *Report of the World Commission on Environment and Development: Our Common Future (“Brundtland Report”)*, <https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf> (accessed August 2025).
41. J. Huber, *J. Environ. Policy Plann.*, 2000, **2**(4), 269.
42. S. Holm and E. Stokes, in *Encyclopedia of Applied Ethics*, ed. R. Chadwick, Elsevier, London, 2nd edn, 2012, pp. 569–575.
43. European Union (EU), <https://eur-lex.europa.eu/EN/legal-content/glossary/precautionary-principle.html> (accessed August 2025).
44. L. Persson, B. M. Carney Almroth, C. D. Collins, S. Cornell, C. A. de Wit, M. L. Diamond, P. Fantke, M. Hassellöv, M. MacLeod, M. W. Ryberg, P. S. Jørgensen, P. Villarrubia-Gómez, Z. Wang and M. Z. Hauschild, *Environ. Sci. Technol.*, 2022, **56**, 1510.
45. United Nations Environment Programme (UNEP), *Green and Sustainable Chemistry Framework Manual*, <https://www.unep.org/resources/toolkits-manuals-and-guides/green-and-sustainable-chemistry-framework-manual> (accessed January 2025).
46. European Commission, *Strategic Research and Innovation Plan for Safe and Sustainable Chemicals and Materials*, Publications Office of the European Union, Brussels, 2022.

47. International Sustainable Chemistry Collaborative Centre, <https://isc3.org/page/sustainable-chemistry/key-characteristics-of-sustainable-chemistry> (accessed August 2025).
48. P. G. Mahaffy, S. A. Matlin, T. A. Holme and J. MacKellar, *Nat. Sustainability*, 2019, **2**, 362.
49. Z. Wang, A. M. Buser, I. T. Cousins, S. Demattio, W. Drost, O. Johansson, K. Ohno, G. Patlewicz, A. M. Richard, G. W. Walker, G. S. White and E. Leinala, *Environ. Sci. Technol.*, 2021, **55**, 15575.
50. Z. Wang, G. W. Walker, D. C. G. Muir and K. Nagatani-Yoshida, *Environ. Sci. Technol.*, 2020, **54**, 2575.
51. E. Kristiansson, J. Coria, L. Gunnarsson and M. Gustavsson, *Environ. Sci. Policy*, 2021, **126**, 90.
52. European Environment Agency, <https://www.eea.europa.eu/en/analysis/publications/pfas-in-textiles-in-europes-circular-economy/figure-3-level-of-knowledge-of-human-health-and-environmental-impacts-of-pfas> (accessed August 2025).
53. G. Goldenman, M. Fernandes, M. Holland, T. Tugran, A. Nordin, C. Schoumacher and A. McNeill, *The cost of inaction. A socioeconomic analysis of environmental and health impacts linked to exposure to PFAS*, Nordic Council of Ministers, Copenhagen, 2019.
54. V. Obsekov, L. G. Kahn and L. Trasande, *Exposure Health*, 2023, **15**, 373.
55. European Commission (EC), https://environment.ec.europa.eu/strategy/chemicals-strategy_en (accessed August 2025).
56. S. Jensen, A. G. Johnels, M. Olsson and G. Otterling, *Nature*, 1969, **224**, 247.
57. S. E. Fenton, A. Ducatman, A. Boobis, J. C. DeWitt, C. Lau, C. Ng, J. S. Smith and S. M. Roberts, *Environ. Toxicol. Chem.*, 2021, **40**, 606.
58. Organisation for Economic Co-operation and Development (OECD), <https://www.oecd.org/chemicalsafety/risk-management/sustainable-chemistry/> (accessed August 2025).
59. Endocrine Society, <https://www.endocrine.org/topics/edc/what-edcs-are/common-edcs/pfas> (accessed August 2025).
60. Politico, <https://www.politico.com/news/2022/09/13/the-battle-over-who-pays-to-clean-up-chemicals-00056136> (accessed August 2025).
61. The Guardian, <https://amp.theguardian.com/environment/2023/may/12/pfas-forever-chemicals-societal-cost-new-report> (accessed August 2025).

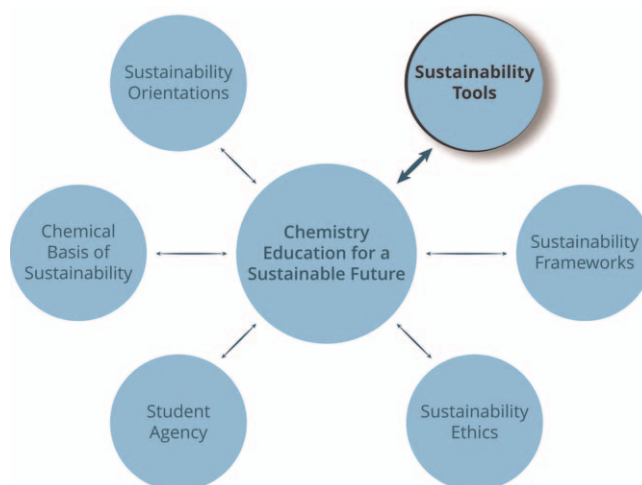
CHAPTER 4

Sustainability Tools I – Systems Thinking[†]

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4.1 Opening Thoughts

Chemistry is often called the “central science” because all citizens need chemical knowledge to make sense of and address the complex phenomena in the world around us.¹ Consider, for example, the United Nations (UN) Sustainable Development Goals.² A knowledge of chemistry seems particularly well-suited for addressing challenges related to the UN sustainability goals of “Zero hunger”, “Good health and well-being”, “Clean water and sanitation”, “Affordable and clean energy”, “Responsible consumption and production”, and “Climate action” (see more in Chapter 7).

Today’s chemistry students can positively impact planetary sustainability in the future. Some of our students will become the scientists and engineers who will directly study and find solutions for challenges related to the Sustainable Development Goals. However, all of our students will need to understand the sustainability challenges we currently encounter and will continue to encounter because they will impact sustainable development, policy, and democratic decision-making for the next 50+ years.

Unfortunately, current research shows that we are teaching chemistry in a way that (1) does not show its connections with other fields and (2) does not equip students with the knowledge necessary to understand and address the complex sustainability challenges they encounter in their everyday worlds. In fact, the authors of recent publications have described chemistry learning as “disconnected”, “fragmented”, “shallow”, “algorithmic”, and “decontextualized”.^{1,3-5} Assuming these descriptors are accurate, our students will not learn chemistry in a meaningful way, let alone be prepared to use their chemistry knowledge to understand and improve the world around them.

Systems thinking approaches can promote meaningful learning of chemistry content while preparing students to become motivated stakeholders who can use their chemical knowledge to address complex global sustainability challenges.^{1,4-8} In fact, the skills developed through systems thinking approaches can be useful both within and beyond chemistry, helping students to (1) identify and visualize the relationships and interactions between the parts in a “system”, (2) recognize how the interactions among the parts of the system lead to the emergent properties of the system, and (3) relate what they are learning in their classes to real-world, bigger picture issues and phenomena.^{4,6,7} In other words, through systems thinking approaches, educators can facilitate the growth of today’s students into tomorrow’s responsible global supporters of sustainability initiatives.

4.2 Background

In general, systems thinking is defined as “a holistic approach for examining complex, real-world systems, in which the focus is not on the individual components of the system but on the dynamic interrelationships between the components and on the patterns and behaviors that emerge from those interrelationships”.⁶ This approach has been used by professional scientists,

engineers, and business people to make sense of complex problems in the world⁹ and has more recently been recommended for and gained more traction for use in chemistry education contexts.^{1,3,5,10-15}

4.2.1 Benefits and Challenges of Systems Thinking

Evidence supporting the use of systems thinking approaches comes from multiple STEM disciplines, particularly from the life sciences and geosciences, in which systems thinking has a longer history of use.⁶ Research from these disciplines shows that systems thinking approaches have both cognitive and affective benefits.^{4,6,7,16,17} For example, a systems thinking approach has been shown to promote meaningful learning of STEM content, increasing both students' motivation to learn and their retention of content.^{16,18-26} It has been shown to help students develop the knowledge and critical thinking skills they need to reason about scientific phenomena.^{21,23,24,27-30} Finally, it has been shown to prepare students to understand and address complex, interdisciplinary, real-world problems in order to, for example, promote planetary sustainability.^{16,17,24,31-40}

In the context of *chemistry* education, systems thinking has been shown to have a number of benefits for both instructors and students.^{10,11,13,15} In general, instructors who were interviewed about the use of systems thinking approaches in chemistry education identified many of the same benefits for students that were described in the previous paragraph. In addition, they said that a systems thinking approach

- motivates students to learn chemistry concepts;
- helps students understand complexity;
- develops students' professional skills in areas such as collaboration, communication, and leadership; and
- develops a desire in students to use their chemistry knowledge to take action to address real-world problems.

They reported that their students seemed to understand chemistry content better, were less likely to fail and more likely to be retained than when they taught *via* more traditional methods.

Interviewed chemistry instructors reported that *they* also benefitted from teaching *via* a systems thinking approach.¹⁵ Primarily, the instructors discussed how this approach required them to learn new content and to figure out ways to connect that content, allowing them to keep content fresh for them and their students. Instructors expressed a belief that systems thinking improved their chemistry course and teaching practices and said that it was enjoyable to teach *via* this approach.

Of course, the interviewed chemistry instructors identified some challenges for students and instructors. For example, the instructors reported that systems thinking requires students to consider chemistry content in new, complex ways, which may be difficult, uncomfortable, or

overwhelming.^{10,11,13,15} However, the instructors who previously had implemented systems thinking approaches in their chemistry classrooms were careful to say that, even though systems thinking is difficult for students, it is valuable for students to learn how to think about complex phenomena.¹⁵

Instructors also expressed concern that they might not know enough about systems thinking or have access to enough resources or time to implement this approach.^{10,11,13–15} As a consequence, in order to teach *via* a systems thinking approach, they had to both learn new content and new ways of thinking. The curious thing, though, is that they found this both a challenge (in that it required time and effort) and a benefit (in that it allowed them to explore new material and present course content in new ways).¹⁵ Overall, instructors with previous experience implementing a systems thinking approach in their classrooms expressed that the potential advantages of using a systems thinking approach in chemistry classes outweigh the potential disadvantages.¹⁵

4.2.2 Essential Characteristics of Systems Thinking

The definition of “systems thinking” provided at the beginning of Section 4.2 is one of many. In fact, a search of the literature or internet will reveal multiple definitions of systems thinking. Primarily, systems thinking is defined as “the ability to understand and interpret complex systems”.⁴¹ Understanding and interpreting complex systems involves (1) visualizing the relationships between the parts in the system;²⁴ (2) examining behavior that changes over time;²³ and (3) examining how systems-level phenomena emerge from interactions between the system’s parts.⁴² Systems thinking has been referred to as an analytic technique for examining phenomena;²³ a problem-solving, visualization, or communication tool;³⁵ or a cognitive skill for explaining natural phenomena.^{7,15,29,43}

While the fact that there are multiple ways of defining “systems thinking” might be confusing, these definitions share some common characteristics. York and Orgill refer to these as the five “essential” characteristics of systems thinking (Box 4.1).⁷

First, systems thinking provides guidance about what students should focus on in order to develop an understanding of the causes of chemical phenomena. For example, systems thinkers in chemistry education should (1) *recognize a system as a whole, not just as a collection of parts*, and (2) *examine the relationships between the parts of a system and how those interconnections lead to the behavior of the system*. This is extremely important because a system as a whole may have emergent properties that cannot be ascribed to any one of the parts of the system.

Next, systems thinking asks students to consider that systems are not static, but dynamic—meaning that they change over time—and to *examine the multiple variables and feedback loops that cause the dynamic behaviors of the system*. A knowledge of how system behaviors change over time,

Box 4.1 Essential characteristics of systems thinking.

A systems thinker in chemistry education should:

1. Recognize a system as a whole, not just a collection of parts.
2. Examine the relationships between the parts of a system and how these interconnections lead to cyclic system behaviors.
3. Identify variables that cause system behaviors, including unique system-level emergent behaviors.
4. Examine how system behaviors change over time.
5. Identify interactions between a system and its environment, including the human components of the environment.⁷

along with an understanding of the causes of the complex behaviors, allows for a deeper understanding of the causes of a behavior. It also provides a foundation for predictions about future behaviors of the system or predictions about behaviors of the system under another set of conditions.

Finally, systems thinking situates chemistry content in a real-world context. The world is a complex place, so, out of necessity, we identify “boundaries” for any system we study. The system influences and is influenced by its environment—including other “scientific” parts of the environment, as well as legal, political, social, and economic components of the environment. In many chemistry classes, we, as educators, tend to focus on the details of the chemical system we are studying, but we often forget to *consider how the system influences and is influenced by its environment*.

Think about how powerful it could be to involve students in these five essential characteristics of systems thinking. If students understand how and why a system behaves as it does, they also will be able to propose changes that will result in a desired outcome. Complex global sustainability challenges like pollution and climate change become not just big, complex problems, but problems that we can do something about!

To further clarify a systems thinking approach in the context of a chemistry classroom, York and Orgill developed the **Characteristics Essential for designing or Modifying Instruction for a Systems Thinking approach (ChEMIST) table (Table 4.1)**.⁷ This table connects the essential characteristics of systems thinking with research-based cognitive skills and tasks in which students can engage while addressing the essential characteristics. The left-hand column of the table lists the essential characteristics of systems thinking. Each of the essential characteristics is associated with three cognitive skills. These cognitive skills are organized on a continuum from more analytical (meaning more focused on the individual parts or components of a system) on the left to more holistic on the right. It might be tempting to think that students should only be engaging in the most holistic of skills, but research has shown that

Table 4.1 The Characteristics Essential for Designing or Modifying Instruction for a Systems Thinking Approach (ChEMIST) table. Reproduced from ref. 7 with permission from American Chemical Society, Copyright 2020.

Systems Thinking Skills		More Holistic	More Analytical/Elaborative
A systems thinker in chemistry education should...		Less Holistic	More Analytical/Elaborative
Recognize a system as a whole, not just as a collection of parts	Identify the individual components and processes within a system	Examine the organization of components within the system	Examine a system as a unified whole
Examine the relationships between the parts of a system, and how those interconnections lead to cyclic system behaviors	Identify the ways in which components of a system are connected	Examine positive and negative feedback loops within a system	Identify and explain the causes of cyclic behaviors within a system
Identify variables that cause system behaviors, including unique system-level emergent behaviors	Identify the multiple variables that influence a given system-level behavior; consider the potential effects of stochastic and "hidden" processes on the system-level behavior	Examine the relative, potentially non-linear, effects that multiple identified variables have on a given system-level behavior	Identify, examine, and explain (to the extent possible) emergent system-level behaviors
Examine how system behaviors change over time	Identify system-level behaviors that change over time	Describe how a given system-level behavior changes over time	Use system-level behavior-over-time trends under one set of conditions to make predictions about system-level behavior-over-time trends under another set of conditions
Identify interactions between a system and its environment, including the human components of the environment	Identify and describe system boundaries	Consider possible effects of a system's environment on the system's behaviors; consider how the system under study might be a component of and contribute to the behaviors of a larger system	Consider the role of human action on current and future system-level behaviors

deeper, more meaningful learning occurs when students use both analytical and holistic skills.^{44–47} In other words, students should engage in a variety of analytical, intermediate, and holistic skills in a given activity or course.

In the next two sections, we will (1) demonstrate how the ChEMIST table can act as a guiding framework when modifying a first-year chemistry topic for a systems thinking approach and (2) show how a systems-oriented visualization and mapping approach can be used to connect chemistry content to both planetary systems and real-world socio-scientific issues.

4.3 Teaching & Learning a Sustainability Topic – Ocean Acidification

A first step in modifying an existing pedagogical lesson or unit in order to make it more systems thinking oriented is to situate chemistry content in an appropriate real-world context. Educational research literature shows that contextualizing chemistry content motivates students to learn science and promotes their abilities to see connections between chemistry and the real world and their abilities to retain knowledge.^{48–52} However, simply adding context should not be the end result if you want to make your classroom teaching more systems thinking oriented.

In this section, we discuss how the essential characteristics of systems thinking listed in the ChEMIST table can be used to iteratively add aspects of a systems thinking approach to an existing lesson about acid–base chemistry, a topic typically taught in either a first-year chemistry or upper-secondary chemistry course. As students learn about this topic, they are introduced to concepts and calculations related to pH, the strengths of acids and bases, and the effects of pH on the solubility of ionic compounds.

Our starting point for the modifications is a module developed by the Visualizing the Chemistry of Climate Change (VC3) project, which teaches acid–base concepts in the context of ocean acidification.⁵³ In the next sections, our goal is not to present a completely modified version of the acids and bases module; rather, it is to show *how* one could take any existing pedagogical unit and modify it through small, iterative steps to make it more systems thinking oriented.

4.3.1 An Overview of Ocean Acidification

Since the Industrial Revolution and as a consequence of both the increased use of fossil fuels and land use changes, such as deforestation, the concentration of carbon dioxide has increased substantially in the Earth's atmosphere. The ocean absorbs 25–30% of atmospheric carbon dioxide, and as a result of the increased atmospheric levels of carbon dioxide, the ocean is absorbing more carbon dioxide than ever before.^{54–56} This increased uptake

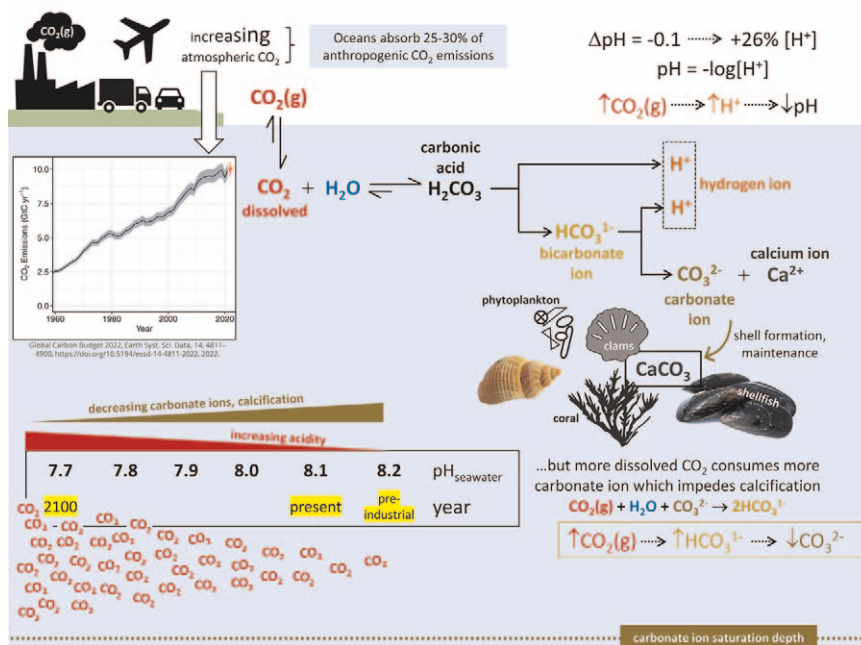


Figure 4.1 Visualization of the chemical processes affecting ocean acidification.

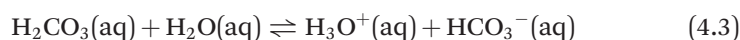
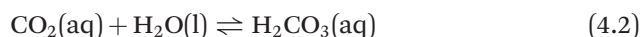
of carbon dioxide has two important consequences: (1) the pH of the ocean is decreasing (becoming more acidic), and (2) the amount of available carbonate ions in the ocean is decreasing.

The ocean is naturally slightly basic. Prior to the Industrial Revolution, the average pH of the ocean was around 8.2. Currently, the pH of the ocean is approximately 8.1. While a decrease of 0.1 pH unit may not seem large, remember that pH is measured on a logarithmic scale ($\text{pH} = -\log[\text{H}_3\text{O}^+]$), so a change of 0.1 pH unit represents a 26–28% increase in acidity. Although the pH of the ocean certainly has increased and decreased over the course of history, the rate of the current decrease in pH is greater than it has ever been in the past. It is predicted that, without intervention, the pH of the ocean will drop another 0.3–0.4 pH units by the end of the current century.⁵⁶

Although multiple chemical species determine the pH of the ocean, in this section, we present the chemical reactions that are causing the pH of the ocean to decrease as a result of the increased concentration of atmospheric carbon dioxide.⁵⁵

A series of related chemical equations result in a decrease in the pH of the ocean and the amount of available carbonate ions (CO_3^{2-}) in the ocean (Figure 4.1). First, gaseous carbon dioxide dissolves into the ocean (eqn (4.1)). Second, the dissolved carbon dioxide reacts with water to form carbonic acid (H_2CO_3) (eqn (4.2)). Third, carbonic acid, a weak acid with a K_a of 4.2×10^{-7} ,

dissociates to form a hydronium ion (H_3O^+) and hydrogen carbonate (bicarbonate) ion (HCO_3^-) (eqn (4.3)).



The increased hydronium ion concentration that results from eqn (4.3) lowers the pH of the ocean. Some of the hydronium ions react with carbonate ions in the ocean to form additional hydrogen carbonate ions (eqn (4.4)), and in the process reduce the amount of carbonate in the ocean that is available for other reactions, such as for the formation of calcium carbonate (CaCO_3 , eqn (4.5)).



The drop in pH and decrease in carbonate ion concentration have deleterious effects on marine organisms, particularly on calcifying organisms and organisms that are pH sensitive.^{55,57} Calcifying organisms—like oysters, clams, scallops, pencil urchins, calcifying zooplankton, and coral—take up carbonate ions from seawater to form calcium carbonate, an important component of their shells or skeletons (see eqn (4.5)). At lower pH levels, with fewer carbonate ions available, it is difficult for these organisms to build their shells or for coral to build their skeletons. When carbonate is particularly undersaturated in seawater, as can happen in cold water regions in which carbon dioxide is more soluble compared to warm water regions, carbonate shells can even begin to dissolve. All of this is, of course, harmful for calcifying organisms; but other marine animals that make coral their homes or that hide from predators in coral also are negatively affected. Interestingly, certain calcifying organisms, like blue crabs, lobsters and shrimp, have been shown to grow thicker shells in lower pH environments.^{58,59} However, it is not known if the extra energy required to grow these thicker shells has negative effects on other biological systems and processes of the animals, for example, their ability to reproduce.⁶⁰

Other marine organisms are pH sensitive. For example, the larvae of some marine organisms do not develop properly at lower pH levels.⁶¹ Some fish larvae lose their ability to smell predators at lower pH levels.⁶² Dungeness crabs lose their ability to detect food at lower pH levels.⁶³ Each of these effects could result in a lower proportion of the organisms surviving into adulthood. Other organisms become more productive in lower pH environments. For instance, harmful algae can produce more toxins in more acidic waters, endangering other marine species and potentially contaminating the food sources of animals in their food webs.⁶⁴ Overall, calcifying organisms are the base of several

marine food webs. Therefore, a population decrease or a contamination of calcifying organisms will negatively affect other species in those food webs.

Because humans and the oceans are connected, Falkenberg and colleagues project that the reduction of both ocean pH and carbonate ion availability in sea water will have several negative effects on humans.⁶⁵ Some of these effects will be physical, including malnutrition/poisoning and respiratory issues. With a smaller proportion of marine organisms surviving into adulthood, there will be less seafood available, a major source of protein for many humans. The seafood that is available (1) may become contaminated or (2) may not be as nutritious as it was previously because pH can affect the types of lipids and proteins formed by marine organisms. When the toxins produced by harmful algae are aerosolized in coastal areas, humans in those areas could develop respiratory issues.

Other effects will be psychological in nature. There will be losses of jobs and livelihoods associated with fishing industries or tourism related to coastal/oceanic activities. There will also be a disruption of nature-based exercise and relaxation and the social connections that are built during these activities.

Overall, human health and well-being will be affected by ocean acidification. It is also worth noting that ocean acidification will likely have a more negative effect on vulnerable populations who (1) do not have funds to pay for alternative foods, (2) cannot procure needed medicines, or (3) cannot move away from contaminated coastal areas.

4.3.2 Connections between Ocean Acidification and Foundational Chemistry Curricula

Multiple connections exist between the content of chemistry courses and ocean acidification. For foundational chemistry, three examples of these connections are presented in Box 4.2. These examples offer the opportunity to

Box 4.2 Connections between ocean acidification and foundational chemistry.

Ocean acidification	Topics in foundational chemistry courses
CO ₂ as an atmospheric gas	The Keeling Curve, ppm The carbon cycle Chemical reactions, stoichiometry Fuel combustion
CO ₂ dissolved in the ocean	Acids & bases Le Chatelier's principle The pH scale, pH calculations
Calcium carbonate in the ocean	Ionic compounds Solubility of ionic compounds Solubility of gases

create a variety of class explorations. For example, in reviewing combustion reactions, an instructor could have students explore how burning fossil fuels has changed the concentration of carbon dioxide in the atmosphere. An instructor could use the chemical equations involved in ocean acidification as examples when discussing the definitions of acids and bases, conjugate acids and bases, acid/base dissociation equations, or the strength of acids and bases. Instructors also could use topics in equilibrium to have students explore why (1) an increase in atmospheric carbon dioxide (a disturbance or stress on a system at equilibrium) would eventually result in an increased amount of hydronium ions in the ocean, or (2) a decrease in the amount of carbonate ions in seawater would result in the dissolving of the calcium carbonate-based shells of calcifying organisms. Additional ideas can be found in the VC3 Acids and Bases module on which this section was modeled.⁵³

4.3.3 Using the ChEMIST Table to Iteratively Make Existing Lessons or Units More Systems Thinking Oriented

Let's say that you have found a perfect context for teaching a chemistry concept. What is the next step for making your teaching more systems thinking oriented? It might be tempting to think that you need to switch to a complete implementation of systems thinking all at once, but the advice that we have received from instructors is to integrate *aspects* of systems thinking into your teaching iteratively (see Practical Suggestion #1 (Box 4.3)).

Once you are comfortable with one small change, make another, perhaps addressing a different essential characteristic or asking students to use different analytical skills than holistic skills. Following this method, your teaching will slide toward being systems thinking oriented, without the process being overly taxing on you or on your students.

The ChEMIST Table (Table 4.1) can be a useful guide for your iterations. Pick one essential characteristic of systems thinking on which you want your students to focus. Next, look at the cognitive skills associated with that essential characteristic. Choose one of the three cognitive skills and look for ways that you can slightly alter your current teaching methods so that students can engage in that cognitive skill in some way.

Next, we will describe three examples of how this could be done with the VC3 Acids and Bases lesson (Sections 4.3.3.1–4.3.3.3). You will notice that the changes that we recommend are simple ones. This is intentional! For a

Box 4.3 Practical Suggestion #1.

When making changes:

- Add something small.
- Try it out.
- See how your students react to it.
- Modify it if needed.

systems thinking approach to be implemented in a sustainable way, it is best to start with small changes that can be added to or made more challenging over time. You, as the instructor, will know what is most helpful and most doable for your group of students. Ideally, after a series of iterations, your teaching will address each of the essential characteristics of a systems thinking approach in chemistry education *and* will ask students to engage in a variety of cognitive tasks that range from more analytical to intermediate to more holistic.

4.3.3.1 *Essential Characteristic and Cognitive Skill Addressed in the First Modification of the Acids and Bases Module*

Essential characteristic of systems thinking: A systems thinker in chemistry education should recognize a system as a whole, not just as a collection of parts.

Cognitive skill (more holistic): Examine a system as a unified whole.

The current version of the VC3 Acids and Bases module explains chemistry content in the context of ocean acidification.⁵³ In other words, the current module tells students how the chemistry they are learning fits within a larger Earth system and tells the students why they should be concerned about decreasing ocean pH. In a sense, the current module is already *telling* students about the Earth system as a unified whole. However, there might be opportunities to *engage* students more directly in examining and finding out more about why ocean acidification matters. Of course, an instructor could send their students off to do an internet search on ocean acidification and its effects; but we recommend giving students a starting place for their examinations. For example, an instructor could introduce students to United Nations Sustainable Development Goal 14—Life Below Water: “Conserve and sustainably use the oceans, seas, and marine resources”—and ask the students to write a short paragraph about the connections between ocean acidification and this UN Sustainable Development Goal.⁶⁶ In addition to helping students examine chemistry concepts within a larger Earth system, this brief task could also be used to develop students’ written communication skills.

4.3.3.2 *Essential Characteristic and Cognitive Skill Addressed in the Second Modification of the Acids and Bases Module*

Essential characteristic of systems thinking: A systems thinker in chemistry education should identify variables that cause system behaviors, including unique system-level emergent behaviors.

Cognitive skill (more analytical): Identify the multiple variables that influence a given system-level behavior; consider the potential effects of stochastic and “hidden” processes on the system-level behavior.

As a part of “Key Idea 3: Acidity, Basicity and the pH Scale”, the current version of the VC3 Acids and Bases module introduces students to

Le Chatelier's Principle.⁵³ In a classroom, an instructor might explain Le Chatelier's Principle and show examples of how different disturbances (or stresses) cause shifts in a chemical reaction that was previously at equilibrium (*e.g.*, the effects of increasing the concentration of reactant, decreasing temperature, or of increasing pressure). At this point, the instructor could provide students with the chemical equations involved in ocean acidification (eqn (4.1)–(4.3)) and ask students to make predictions about disturbances that would increase or decrease the amounts of the carbon species involved in ocean acidification.

For example, the instructor might ask questions such as these: “Which disturbances or stresses would cause an increase in the amount of hydrogen carbonate in seawater? Which disturbances or stresses would cause a decrease in the amount of hydrogen carbonate in seawater? Consider how changes in pressure, temperature, and reactant or product concentrations might affect the amount of hydrogen carbonate in seawater”.

The instructor might also extend this activity by asking students to predict how, for example, the amount of hydrogen carbonate found in cold water regions might compare to that found in warm water regions—and to think about the consequences of this information.

A systems thinking approach directly involves students in identifying the variables that influence a system behavior of interest. As a consequence, an activity such as this can help students start to think about steps they and others can take to address challenges to planetary sustainability.

4.3.3.3 *Essential Characteristic and Cognitive Skill Addressed in the Third Modification of the Acids and Bases Module*

Essential characteristic of systems thinking: A systems thinker in chemistry education should identify interactions between a system and its environment, including the human components of the environment.

Cognitive skill (intermediate): Consider possible effects of the system's environment on the system's behaviors; consider how the system under study might be a component of and contribute to the behaviors of a larger system.

A good way to help students visualize the relationships between system components involved in ocean acidification (*e.g.*, atmospheric carbon dioxide concentrations, concentrations of carbonate ions in seawater, ocean pH, and the ability of calcifying organisms to construct their shells and skeletons) and how those system components might be connected to parts of the system's environment (*e.g.*, the burning of fossil fuels, deforestation, environmental policies, fishing industries, human health, and food sources) is to ask students to show the connections between the system and its environmental components in a Systems Oriented Concept Map Extension, a SOCME (“sock-me”). Students can draw their SOCMEs by hand or they can use the online SOCKit tool⁶⁷ to create a SOCME. The generation of a SOCME

can help students organize their ideas about the multiple variables that influence and are influenced by the system they are studying. Once created, students can use their SOCMEs to think through and propose human actions that can be taken to slow the rate of ocean acidification. In other words, the creation and use of a SOCME can help students not only to better understand ocean acidification but also to consider actions they can take to address this challenge to planetary sustainability!

We hope you can see that, through small iterations, your teaching can be shifted toward a more systems thinking approach. As a final note, it is worth examining your current teaching and lessons *before* you modify them. It is entirely possible that you are *already* addressing some of the essential characteristics of systems thinking! If, for instance, you find that you are already addressing the first, third, and fourth essential characteristics in your teaching, you might want to focus your future modifications on addressing the second and fifth essential characteristics.

4.4 Teaching & Learning a Sustainability Topic – Lithium-ion Batteries

As described in the previous example, when chemistry teaching and learning is situated within an appropriate real-world context, this is itself a systems thinking approach, albeit a limited and surface-level implementation. The ChEMIST table demonstrates how educators can iteratively incorporate additional aspects of a systems thinking approach into their classroom teaching.

A systems thinking approach has the potential of helping students understand content better; however, we also know that engaging in systems thinking can be quite challenging for students who are new to it.^{68,69} The further we drill down into the levels of chemistry, the more we become aware of how complex chemistry can be. Simplistic explanations of phenomena (*e.g.*, metals are malleable, metals conduct electricity) only hold when a single *scale* or system level is investigated. Given that chemistry content is never really one system, but rather is better understood as a series of systems, what we are really studying is the relationships *within* and *among* these different systems or subsystems. These systems/subsystems then make up the *whole* system, which has emergent properties based on these relationships. For instance, sustainability has been referred to as an emergent property of the whole system; in this instance the “whole system” might perhaps be the planet.⁷⁰

How can we use different systems and perspectives to help students understand both chemistry and the influence of chemical processes on the Earth or its inhabitants? Two general approaches exist. The first is to look at chemical processes at different scales, for instance the macroscopic, particulate, molecular, atomic and sub-atomic/electronic levels. Here the task is to “zoom in” or “zoom out” to notice patterns or relationships not immediately evident at a certain level or scale.⁷¹ The second approach is to look at the interactions between chemical processes and different science/Earth

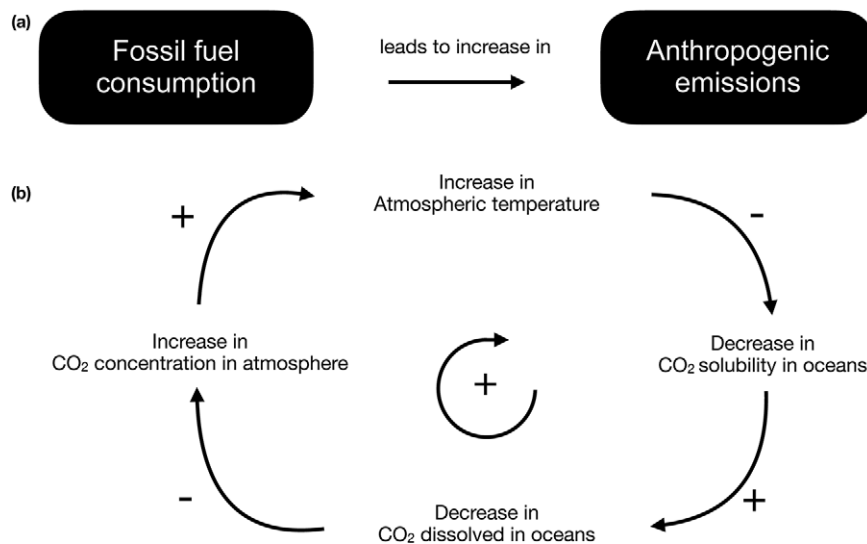


Figure 4.2 A simplified concept-connection-concept relationship (top, a). An example of a positive feedback loop in the oceans (bottom, b). (b) Adapted from ref. 71 with permission from American Chemical Society, Copyright 2019.

subsystems (for example chemical, biological, physical, environmental) and/or human-level subsystems (for example social, political, ethical, legal, economic, cultural). In essence, this approach connects chemical ideas with the broader impacts of a context, which could include the impact of chemical processes on human social networks or on the environment.⁵

Many efforts to incorporate systems thinking into chemistry education have used *visualization* or *mapping approaches* to represent (1) the different scales or subsystems of a chemistry context and (2) the relationships between components of those subsystems.⁷² These mapping approaches can include labeled arrows to signify the nature of relationships or $+/-$ labels to signify how one variable affects another. Figure 4.2a and b show simplistic representations of two of these systems thinking visualizations. Figure 4.2a visualizes a connection between two concepts, and Figure 4.2b visualizes the impact of a positive feedback loop taking place in the oceans, similar to that shown in Figure 4.1.

Systems maps,⁷³ systemigrams,⁷⁴ and systems-oriented concept map extensions (SOCMEs)⁷⁵ have been implemented in educational settings to connect core chemical content with broader multi-system impacts of learning.^{69,76} With these maps, students are challenged to consider questions related to:

- the energy and mass requirements for a chemical process or product;
- what happens with not only the intended product but also the by-products and waste heat; and
- the unintended consequences of utilization (or over-utilization, or over-reliance) of a chemical process or product.^{68,77}

With these visualization and mapping techniques, one can demonstrate how and why a decision about a chemical process and its product(s) is rarely just a *scientific* one. Decisions made with respect to energy and mass inputs (*e.g.*, Where are these sourced? Who makes these decisions?) and energy and mass outputs (*e.g.*, Who is the product/process for? What benefit does it bring society? How has the utilization of this product/process changed our environmental systems?) are also economic, political, social and environmental ones.

The next activity shows how the building of a SOCME can be used to visualize the connections of core chemical science systems with the broader human systems of our planet and demonstrates the principle of moving “from Silos to Systems”.⁷⁸ This activity could be (1) built over a series of lessons or a unit topic, (2) presented as a collaborative or an individual task, or (3) used in conjunction with a formative or summative assessment where students “fill in the gaps” of a partially constructed SOCME.⁷⁶ The SOCME could be constructed on a large piece of paper, on a whiteboard, or with online concept mapping tools such as *Miro* or *Draw.io*. It could also be constructed with a purpose-built online tool such as SOCKit,⁶⁷ which was used for Figures 4.5–4.11.

The context for the SOCME generation is lithium-ion batteries: how and why they are a component of the “green” energy transition and whether this transition is managed equitably across society.

4.4.1 A Basic Understanding of Lithium-ion Batteries

As the world moves away from carbon-based fuels for ground transportation, EVs (electric vehicles) are becoming more common. Battery electric vehicles (BEVs) do not emit carbon dioxide during utilization because a large lithium-ion battery is their source of power. Lithium-ion batteries are commonly used to power electric vehicles because of their high energy density, rechargeability, and low self-discharge rate.

How do lithium-ion batteries work? A typical electric vehicle (EV) lithium-ion battery is made up of two electrical current collectors, two electrodes (cathode and anode), a separator, and an electrolyte. A schematic drawing (not to scale) shows the main components of a typical lithium-ion electric vehicle battery and the movement of both electrons in an external circuit and the positively charged lithium ions (Li^+) in the battery encasement during battery discharge and charge (Figure 4.3). The two electrode current collectors are identified with different fill patterns, denoting two different metals.

During discharge, the movement of Li^+ from the anode to the cathode compartment through the separator creates free electrons in the anode that flow through the external circuit to the cathode current collector. Between the anode and cathode current collectors is the load, all the parts of the vehicle that require an electrical current to operate: dashboard electronics; in-car computer system; internal and external lighting; windshield wipers; moving seats; and, of course, the propulsion system that ultimately moves the tires forward or backward.

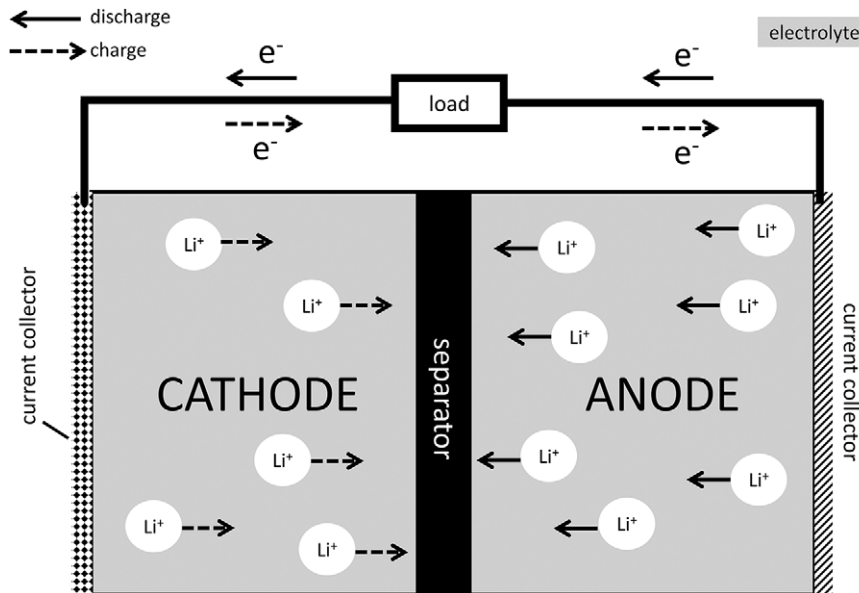


Figure 4.3 Schematic of a typical lithium-ion battery used in battery electric vehicles (BEVs).

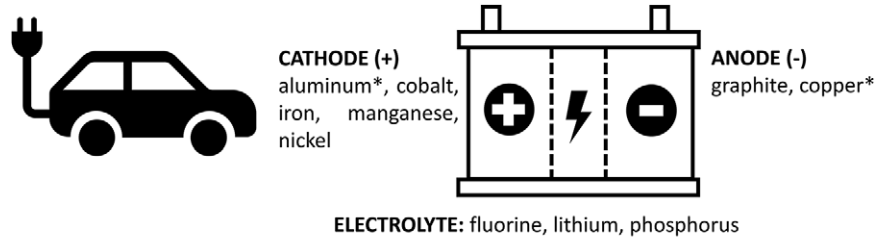
Lithium-ion batteries can vary in the composition and ratio of the electrode materials, size, the metals used as current collectors, the electrolyte composition, and more. These differences in Li-ion vehicle batteries translate into differences in:

- | | | |
|--|--|--|
| <ul style="list-style-type: none"> • Overall weight • Charge–discharge rates | <ul style="list-style-type: none"> • Performance at hot/cold temperatures • Total number of times it can be charged (life cycle) | <ul style="list-style-type: none"> • Distance EV can travel before charging • Cost, as some materials are more expensive than others |
|--|--|--|

The most common materials for the construction of EVs are shown in Figure 4.4. The exact ratio of materials used in EV lithium-ion batteries – particularly the cathode component – results in the many variations of lithium-ion batteries. Some common types include:

- lithium cobalt oxide
- lithium nickel cobalt aluminum oxide
- lithium iron phosphate

These differences lead to specific applications. For example, lithium cobalt oxide-based batteries are common in consumer electronics while lithium nickel cobalt aluminum oxide chemistries are common in electric vehicle batteries. Common metals used in EV batteries are listed in Table 4.2.



^: anode, cathode, electrolyte, and current collectors; *: used in current collectors

Figure 4.4 Key components in a lithium-ion electric vehicle (EV) battery (modified from ref. 79).

Table 4.2 Metals used commonly in EV batteries, including those designated as critical minerals.^a

	Alumi- num	Cobalt	Copper	Graphite	Iron	Lithium	Mang- anese	Nickel
Used in EV	CC	C	CC	A	C	E	C	C
Critical mineral ^b	YES	YES		YES		YES	YES	YES

^a A = anode; C = cathode; CC = current collector; E = electrolyte.

^b Critical minerals.⁷⁹

Of these metals, aluminum, cobalt, graphite, lithium, manganese, and nickel are listed by the United States Geological Survey (USGS) as critical minerals, meaning that they are vital to the national security and economy of the United States (see Chapter 2). The mining of critical materials to produce an EV is geographically concentrated. A select group of countries account for the overall supply of lithium, with Australia contributing the largest percentage of mining for lithium ore, followed by Chile, China, and Argentina.⁷⁹ While Australia may mine the most lithium, it does not *refine* the lithium ore; instead, Australia ships its ore to China for refining. As such, China can be considered the largest producer of cathode-ready lithium.⁸⁰

In a mere seven years (2015–2022), global electric vehicle sales skyrocketed from 716 000 to 10.6 million vehicles.⁷⁹ This increased the demand for materials to produce lithium-ion batteries. Though projections about future global demand for battery electric vehicles vary among governments and industry groups, they all project global demand for EVs will continue to increase within the next decade.

4.4.2 A Basic Understanding of Lithium Sources, Lithium Processing, and Lithium Refining

Lithium is sourced in two ways, namely hard-rock mining and the evaporation of brine water. For hard-rock mining, the ore spodumene ($\text{LiAlSi}_2\text{O}_6$) is

an important source of lithium. To obtain the spodumene ore, massive open pit mines are dug using impressively large machines. The world's largest hard-rock lithium ore mine is the Greenbushes mine in western Australia, which accounts for 21% of the global lithium resource supply and in 2023 produced 1.52 million tonnes (= metric tons) of concentrate with enough lithium for 3 million EVs, 385 million e-bikes, or 797 million cordless tool batteries.⁸¹ Lithium carbonate is a stable salt that contains unreactive lithium ion (Li^+) and is the most widely traded lithium-based chemical globally, as it is the main material used for the manufacture of EV battery cathodes.

Like lithium ores, lithium-rich brine water is geographically concentrated. One source, which is estimated to hold approximately 50 million of the identified 86 million tons of the world's reserve of lithium, is the salty groundwater located below the world's driest desert, the Atacama, which is located on the west side of South America and spans the countries of Argentina, Bolivia, and Chile (known as the "Lithium" or "ABC Triangle").⁸²

How does it work? The salty (brine), mineral-rich groundwater is pumped to the surface and directed into large open-air evaporation ponds. Over the span of hundreds of days, the water—but not the lithium and other minerals dissolved in the brine—evaporates in the relentless desert heat, in an area where it rarely rains and which has one of the highest solar radiation levels in the world. As the water evaporates, the volume of the brine water decreases and the lithium concentration increases. After 12–18 months, enough water has evaporated that the concentration of lithium is high enough (around 6000 ppm where ppm = parts per million) for the brine water to be transported to a nearby facility where other minerals, such as boron and magnesium, are removed.⁸³ The treated brine water then is processed into solid lithium carbonate (Li_2CO_3) or lithium hydroxide (LiOH). The brine water is considered consumptive water because it is not returned to its place of origin. It is estimated that approximately 568 000 liters of brine water with a mean lithium concentration of 1600 ppm produces 1 ton (2000 pounds) of lithium.⁸⁴

Even though a fully built, post-manufactured BEV does not emit CO_2 while in use, it still has a carbon footprint that is connected to plugging the BEV into the electrical grid, especially if the electrical grid generates electricity from high-carbon sources such as burning (dirty) coal or (much less dirty) natural gas ($\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$). Low-carbon electrical grids utilize nuclear, solar, wind, or hydropower.

And what about CO_2 emissions created during manufacturing of the materials (lithium, nickel, cobalt, manganese, and so on) that comprise an EV's electrodes? Again, consider lithium. CO_2 is emitted during the extraction, transport, and processing of lithium found in hard-rock ore and brine, though the intensity of CO_2 emissions is different between lithium extracted from hard-rock *versus* brine. Collectively, the emissions come from:

- the gasoline and diesel-powered excavation machinery needed to dig wide and deep open pit mines and move rock out of the way;

- the constant parade of massive dump trucks that move tons of excavated ore from the mine to the crushing/milling facility where huge machinery consumes copious amounts of electricity to crush and mill the excavated hard-rock ore;
- the pumps that move sub-surface brine to the surface; and
- the trains and/or cargo ships that transport the crude extracted lithium to processing plants where it is converted into battery grade lithium carbonate or lithium hydroxide, a core starting material for EV battery cathodes.

4.4.3 A Basic Understanding of Lithium Recycling

Lastly, the recyclability of lithium and other metals in end-of-life (EOL) lithium-ion BEVs (LiBEVs) should be considered. Examine the projections and information shown in Table 4.3.

Based on the projection of 11 million metric tons of EOL LiBEVs, coupled with the fact that lithium (not lithium carbonate) comprises 3.5% of the mass of an EOL LiBEV, a quick theoretical computation (excluding recovery rate) indicates that EOL LiBEVs could yield about 385 000 metric tons (849 >million pounds = 385 million kg) of recoverable lithium that does not need to be mined from hard rock or brine and, consequently, could be used again in one of the 140 million new LiBEVs expected to be on the road by 2030.⁸⁵ Recycling is favorable as the cost, energy-intensity, and environmental harm done by recycling is less than that of mining low grade lithium ores. An EOL LiBEV can then be effectively considered as a source of highly enriched ore.

Other recycling benefits include lower battery manufacturing costs as recovered metal – at large scale – is less costly than extracting it from the Earth’s crust. Large scale recycling also smooths out the uncertainties that come with sometimes wild market price fluctuations for metals. For example, battery-grade lithium carbonate was selling for nearly £102 000 (\$85 000 USD)/metric ton in November 2022. A year later, its selling price was around £23 750 (\$19 000 USD)/metric ton. Furthermore, the economic value of EOL LiBEVs will ideally reduce the number of batteries that end up in landfills, where they could possibly contribute – *via* cracked battery casings – to soil and groundwater contamination. Lastly, the recycling of EOL LiBEVs will invariably slow the depletion rate from mining the metals involved.

But other factors in the recycling equation must also be considered. The sometimes wild (and unpredictable) ups and downs of metal prices on the

Table 4.3 Projections of the amount of end-of-life (EOL) lithium-ion BEVs expected by 2030 and the amount of lithium available for recycling.

Number of LiBEVs predicted to be on the road worldwide by 2030 ⁸⁵	Metric tons of EOL LiBEVs expected by 2030 ⁸⁶	Mass % of lithium in EOL LiBEVs	Mass of lithium in BEVs ⁸⁷ (kg)
140 million	11 million	3–4%	6 kg (5–7 kg)

global market present a persistent, unwanted challenge to recycling. For example, if the price of nickel, or cobalt, or lithium drops and stays at the lower price long enough, then EOL battery recycling businesses could have a hard time competing (price wise) with mined metals. The varied metal compositions of the cathodes also present a problem, requiring EV battery recyclers to initially sort lithium-ion battery types before taking further steps to separate and recycle the metals in the batteries. Unfortunately, EV batteries are not designed to be taken apart, come in a spectrum of sizes and shapes, and have battery control circuitry and sensors that need to be separated out in order to get to the metals. The more difficult it is to dismantle an EV battery, the higher the recycling cost.^{86,88}

Ultimately, the constantly varied and changing chemistries of EV batteries means that battery recyclers will need ever-evolving facilities and capacity to efficiently recover materials and operate profitably. The recycling rate of lithium in EOL BEVs could also be positively influenced by increasing interest in recovering BEV components that are relatively easy to recover (aluminum casing, copper wire) or that are in finite supply and which are becoming strategically important (cobalt, nickel).⁸⁶

4.4.4 Connections between Lithium-ion Battery Chemistry and Chemistry Curricula

Students in foundational undergraduate chemistry and upper secondary chemistry are likely to study redox and electrochemistry, and lithium-ion batteries could be either an interesting context for these topics or an example of an application of battery technology. Students investigating the application of redox chemistry in electrochemical cells are likely to engage in a hands-on practical activity in which they build rudimentary galvanic cells, perhaps starting with a Daniell cell made from Zn and Cu electrodes and their respective aqueous solutions, before trying other “half cells” made from a metal electrode extending out of a beaker containing the corresponding metal ion in aqueous solution (*e.g.*, a Cu electrode in a $\text{Cu}^{2+}(\text{aq})$ solution) to vary the potential difference measured (in volts). In doing so, students can compare their experimentally measured voltage with the theoretical potential difference determined from their reading of the electrochemical series.

	E_0 (volts)
$\text{Li}^+(\text{aq}) + \text{e}^- \rightleftharpoons \text{Li}(\text{s})$	-3.03
$\text{K}^+(\text{aq}) + \text{e}^- \rightleftharpoons \text{K}(\text{s})$	-2.92
$\text{Ca}^{2+}(\text{aq}) + 2\text{e}^- \rightleftharpoons \text{Ca}(\text{s})$	-2.87
$\text{Na}^+(\text{aq}) + \text{e}^- \rightleftharpoons \text{Na}(\text{s})$	-2.71

However, students are highly unlikely to build a rudimentary galvanic cell from a half-cell containing lithium metal, given the potential for lithium-ion batteries to catch fire and explode due to thermal runaway.⁸⁹ Therefore, the

application of lithium here will likely be limited to inquiring as to why the $\text{Li}^+(\text{aq}) + \text{e}^- \rightleftharpoons \text{Li}(\text{s})$ half-equation is at the top (or bottom, depending on the representation) of the electrochemical series. Students using terms such as “oxidant” or “reductant” for the first time can learn that $\text{Li}(\text{s})$ is the strongest reductant (or reducing agent) and that $\text{Li}^+(\text{aq})$ is the weakest oxidant (or oxidizing agent) on the table. Later, as part of a lesson sequence involving battery chemistry and the circular economy, students could also learn why the unique redox potential of $\text{Li}(\text{s})|\text{Li}^+(\text{aq})$ makes lithium difficult to chemically separate and recover during battery recycling, compared to other metals present.⁹⁰

Students could also relate lithium’s prominent role in modern battery technology to lithium’s position in the periodic table. Lithium is the lightest and smallest of the metals in the periodic table, giving lithium ions a significant size advantage, compared to, for example, a sodium ion, as it intercalates into the two different structures/sides of a lithium-ion battery, often graphite at the anode and LiCoO_2 at the cathode.⁹¹ Students will likely come across diagrammatic representations of this ion-exchange occurring inside the lithium-ion battery in redox and electrochemistry chapters of their textbooks; but as the actual chemistry explanation is quite complex and the focus of ongoing research, the textbook explanation of this process is likely to be highly simplified. Consequently, it would be sufficient and appropriate for students to develop the capacity to label and name each part of the battery, the role of the electrolyte, the direction of the electron flow, and so on.

It was not until the onset of the “age of electricity” (late 18th/early 19th century) that experimental chemists such as Humphry Davy were able to isolate metals such as lithium, sodium, and potassium in their elemental form by applying massive amounts of electricity to their corresponding metal ions in solution, then quickly storing these elemental metals in a moisture-free environment. The massive amount of electricity required was sourced from rows and rows of electrochemical cells in series, housed nearby to form a room-sized “battery”. These battery rooms did not look that dissimilar to the massive lithium-ion batteries being designed and built worldwide, now on a scale of >1000 MW (megawatts) in size, as part of the global green energy transition. These are being built next to renewable energy production sites to store temporarily the energy produced, which can then be provided to the grid at times when it is most needed.

4.4.5 Using Visualization to Represent Relationships Within and Across Systems and Identify Emergent Properties of a System

The student activity presented in this section was designed for students to investigate how and why lithium-ion batteries are a core component of the green energy transition. Box 4.4 introduces the SOCME student activity, including the learning intentions (worded to align with the essential characteristics of systems thinking, as established in the ChEMIST Table, Table 4.1). Boxes 4.5–4.8 provide further impetus as prompting questions for students to

Box 4.4 Student activity – build a SOCME of a chemical process or product.

In this Systems Oriented Concept Map Extension (SOCME), you will visually represent the components and relationships that make up an overall system. Over the course of developing this SOCME, you will learn to:

- envisage the system more holistically and “as a whole”, and less so as a collection of parts
- identify components in the system and each integrated subsystem, explore the relationships between these components (both within and across subsystems), and so envisage which of these are causing *system-level* behaviors, including those that are only apparent when we look at the “bigger picture”
- identify how individual components and the overall system is having an impact on the environment in which it takes place (*i.e.*, the planetary environment)
- identify and explore the nature of *human-level* interactions with this system, and so envisage how:
 - human decisions and actions impact the behavior of the system, and
 - system-level behaviors impact the nature and behavior of humans.

SOCMEs are normally developed over a number of stages. You may wish to do this individually or collaboratively with your peers. It could be developed on large sheets of paper, by using an online concept mapping tool, or by using a purpose-built tool like SOCKit.⁶⁷

- **Stage 1:** establish the key chemical process or product that you will explore with your SOCME. Your choice could be informed by a key chemical observation for which you wish to explore the wider implications.
- **Stage 2:** identify the key mass and energy inputs for this chemical product/process, and where they are sourced. Identify the intended uses of the chemical product/process, but also explore what happens to the by-products and product waste at end-of-life.
- **Stage 3:** investigate the impact that this chemical process has on the environment, be it on land, in our waters, or in the atmosphere (the three main subsystems that make up our planet). Investigate how the sourcing of feedstocks, the utilization (or over-utilization) of the product/process, and the resultant waste have an impact on the planet.
- **Stage 4:** investigate the human aspects of this system, be they ethical, economic, political, or social considerations. Explore the nature of who benefits from this system, and how. Explore how the system has an impact on how as humans we live, work, and play.

consider as they expand their SOCME. These prompts have been written free of context, so that they can be used by educators wishing to guide students through making a SOCME of their choice. The main body text will provide some additional suggestions for educators, as well as a step-by-step exemplar SOCME on lithium-ion batteries, with the final design shown in Figure 4.11.

Educators and students alike may have had some prior experiences with building concept maps, for which the learning objective is often to diagrammatically present snippets of key knowledge (called “components” here) about a particular theme. In a concept map, it is also important to draw connections between these components (called “relationships” here), either by drawing a line to imply two components are connected in some way, or an arrow pointing from one component to another to imply the first component has an impact on the second. On occasion, the user may write some text adjacent to the line/arrow, to describe the nature of this effect/relationship. Figure 4.5a and b demonstrate some examples of visualizing the relationships between components.

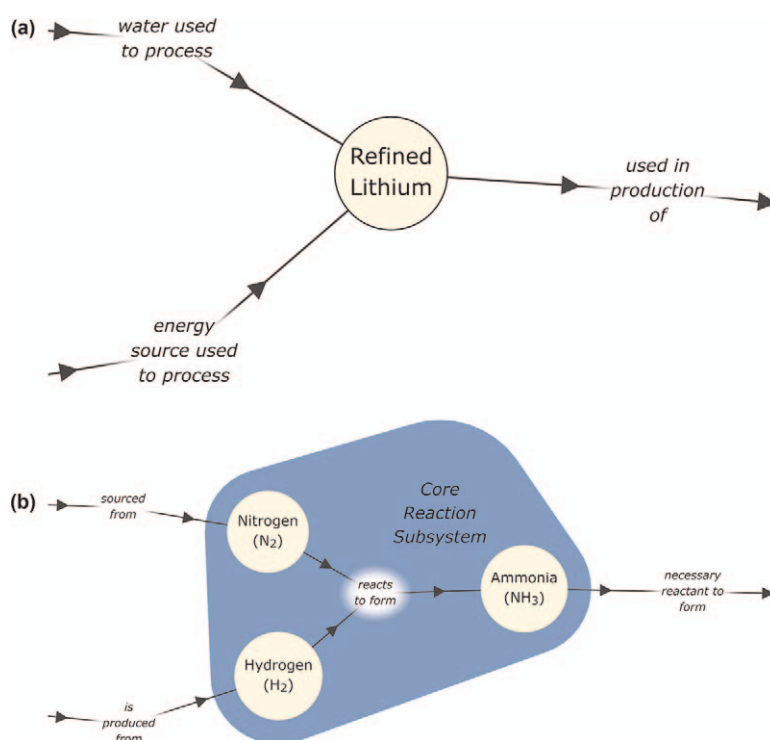


Figure 4.5 Examples of components being connected by arrows and accompanying text to briefly outline the nature of the relationship between the components. (a) (top) Would be typical for a concept map, whereas the (b) (bottom) would be more typical for a SOCME, where the key chemical reaction that produces the product of interest is represented as a “core reaction subsystem” (for example, the Haber Bosch process to produce ammonia).

In any SOCME, the intention is to identify and explore (1) the nature of these relationships and (2) how these relationships impact the overall “system”. In **Stage 1**, it is therefore important to identify first what is the key product, process, or system that is being investigated, for instance the production of CO₂⁷² or the treatment of a particular disease.⁹² Sometimes we might represent this as a single component (as shown in Figure 4.5a, which we will use for the SOCME built here), or as a “core reaction subsystem” (as shown on Figure 4.5b, which shows the production of ammonia *via* the Haber–Bosch process⁷⁷).

With the core theme or central concept established, **Stage 2** of building a SOCME involves exploring in more detail how and why the chemical product is produced, used, and/or disposed of. For a SOCME novice, this next step can feel daunting, so it is best to try to “stick to the chemistry” for a little bit longer. Also look to incorporate prior knowledge from related topics, such as chemical energy and conditions of chemical reactions. Box 4.5 provides some prompting questions that unpack the key chemical product or process and which one can use to start populating the next four subsystems of the SOCME.

Box 4.5 Prompts for students to consider when building reaction subsystems (including energy inputs, mass inputs, intended uses) of a SOCME (Stage 2).

In a subsystem for mass (or chemical) inputs, consider:

- Where does the main feedstock come from? How is this sourced?
- What other reactants are needed? Where do they come from?

In a subsystem for energy inputs, consider:

- What are the energy requirements? How is this sourced? Is there waste heat and what happens to that waste heat?
- What are the reaction conditions? What is needed to maintain these conditions?

In a subsystem for intended uses (i.e., the purpose), consider:

- If the main product of this core reaction subsystem is the chemical of interest, what is it useful for? What are the intended uses of this product?
- If the main product of your core reaction is primarily utilized to produce other things for industry and society, what are they, and what are their intended uses?

In a subsystem for waste and disposal, consider:

- What are the by-products of the chemical process? Are these useful for something else or do they enter a waste stream?
- Are there anthropogenic emissions from the process? How does this relate to how energy is sourced in the production of this product (fossil fuels? renewable energy?)
- What is the product made-to-waste generated ratio?

Figures 4.6 and 4.7 present an example of how one might answer the prompting questions of Box 4.5 if constructing a SOCME about lithium-ion batteries. The knowledge informing the components and relationships draws upon the introduction to lithium-ion batteries described earlier in the chapter. [NOTE: Figures 4.6–4.10 show portions of a detailed, complete

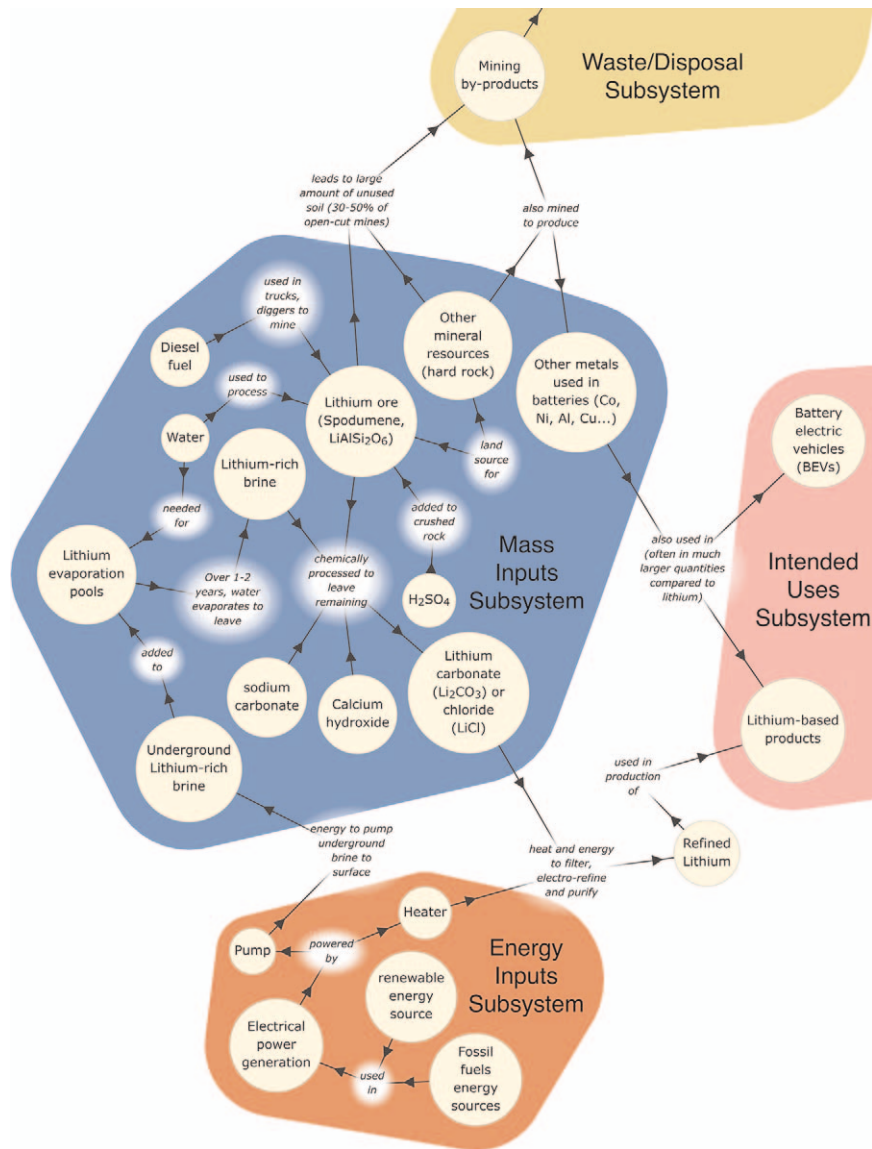


Figure 4.6 A partially constructed SOCME, with lithium as a central node in the middle, shown with the mass and energy input subsystems.

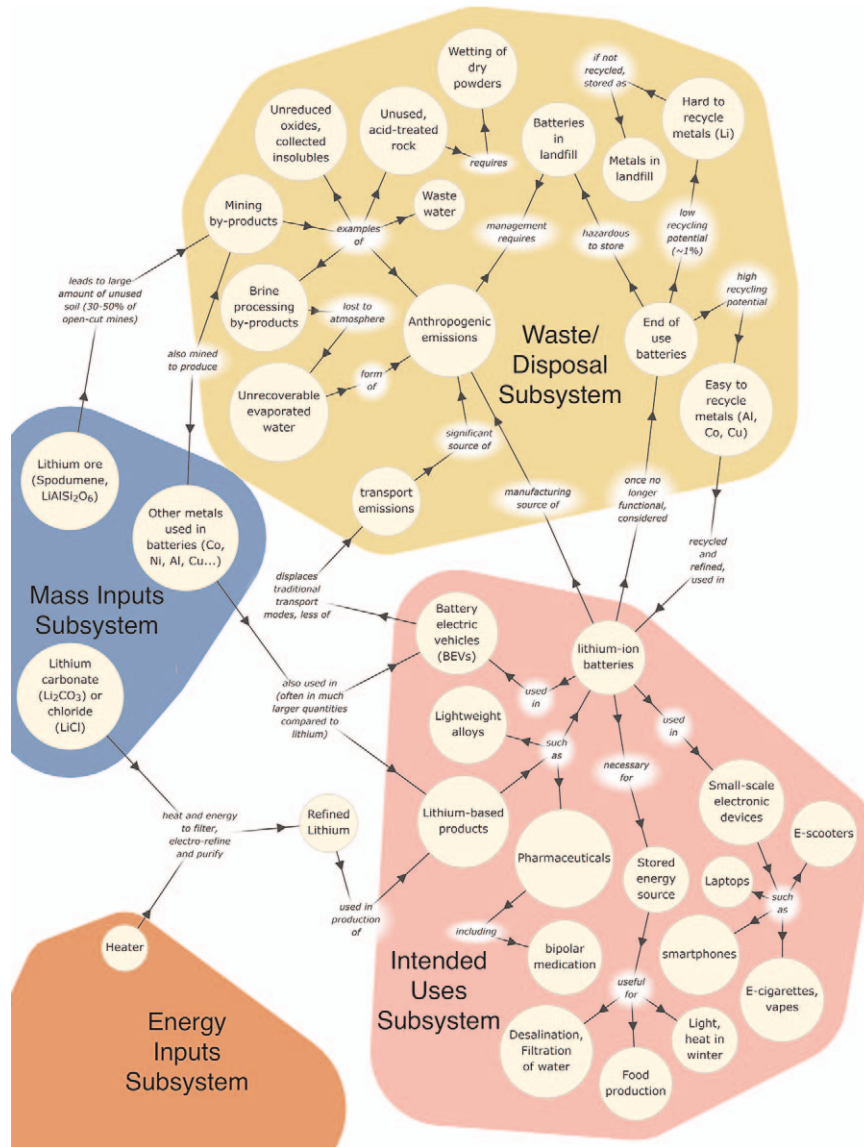


Figure 4.7 A partially constructed SOCME, with lithium as a central node in the middle, shown with the waste/disposal and intended uses subsystems.

SOCME focused on lithium-ion batteries. The complete SOCME can be accessed through the QR code that accompanies Figure 4.11].

There are no rigid rules on how the subsystems are named or formed. In general, however, one might expect to have a subsystem for the mass/chemical inputs of this chemical process/product and another subsystem for the energy requirements, which might also include components related to the reaction

conditions (heat, pressure, catalyst). Another subsystem could present the waste or by-products of this chemical process/product. Lastly, one could include a subsystem for what the chemical process/product of interest is primarily used for; in other words, what is the *intended use* of the chemical product. How the chemical product is used in industry and society will directly tie into the human-level subsystems addressed in a later stage of SOCME development.

In Figures 4.6 and 4.7, note that each arrow has a corresponding brief description of the connection between the two concepts. Whereas the direction of the arrow gives some indication of the *direction* or *flow* of the influence/relationship (*i.e.*, cause and effect), the description provides insight into the *behavior* of the relationship, and so greater insight into the particular subsystem or system. Try to write short, precise descriptions. You may notice that when you write the first few descriptions, you become inspired to make other connections between components already on your SOCME that you did not originally notice. As this process continues, you will start to see how the complexity can begin to be visualized, but in a way that can be interpreted and understood by the user.

If this is already starting to feel daunting, particularly for the first-time student, an educator could engage their students in a simpler version of this Stage 2 task, one in which the students would focus only on making connections between components. In this task, the educator would provide students with a partially constructed SOCME similar to that shown in Figures 4.6 and 4.7 but *without* the connecting statements about the arrows (or possibly even without the arrows as well). Then the educator could task the students with writing in their own description above the arrows or drawing new arrows and describing these new connections. This task would support students in solidifying their understanding of the concepts *while* getting them used to creating a SOCME.

Stage 3 involves connecting with planetary systems, and so to consider the impact of the chemical process/product on *planetary sustainability*. This is where a SOCME or systems map can really stand out compared to a standard concept map. Box 4.6 provides some further prompts you might like to consider for the (main) three subsystems that make up the planetary system,

Box 4.6 Prompts for students to consider when building planetary subsystems (land, aquatic, atmosphere) of a SOCME (Stage 3).

For each of the land, aquatic and atmosphere subsystems consider:

- How does the *sourcing* of reactants/feedstock for this chemical process/product impact the balance of land, aquatic and atmosphere environments?
- How does the accumulation of waste (end-of-use waste, by-products) or related side effects impact the balance of land, aquatic and atmosphere environments?
- How does the *utilization* of the chemical process/product impact the balance of land, aquatic and atmosphere environments?

namely the atmosphere, aquatic environments (the ocean, nearby lakes and rivers, the water table) and land environments.

Figure 4.8 extends the previous stage of the SOCME to now include these three planetary subsystems. See how the acquisition of feedstocks (open-cut mining for lithium ore, groundwater sourcing for brine processing, reliance on fossil fuels) is a predominant feature of the land subsystem. How we deal

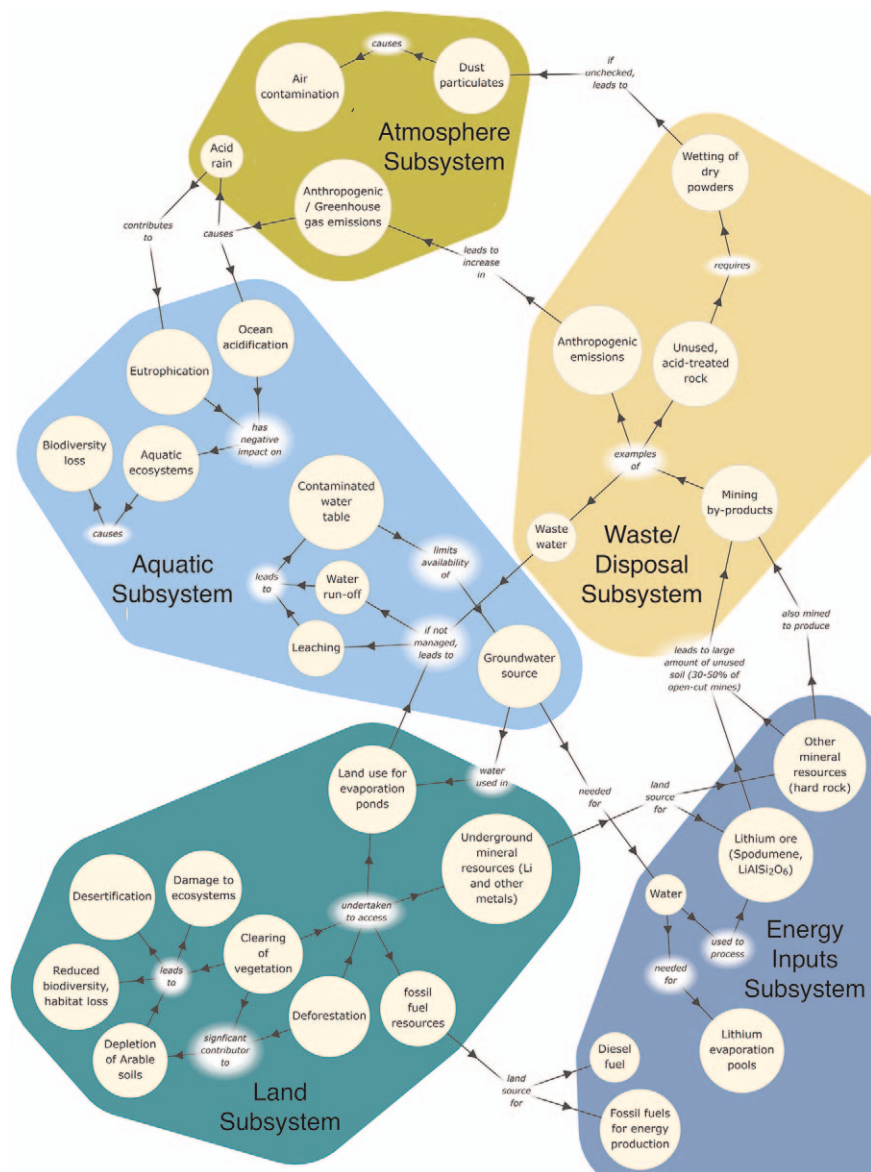


Figure 4.8 A further expanded SOCME, now with land, water and atmosphere subsystems.

(or not sufficiently deal) with the waste from these processes can impact all three subsystems. Consider how waste and by-products are stored on land. Consider the *unintended* side effects of long-term storage or an overabundance of waste. For instance, the run-off of tailings (a by-product of mining) waste can enter water streams and cause contamination. Plastic and micro-plastic debris can find their way into rivers, lakes and oceans and cause significant damage to aquatic ecosystems.⁷⁵ Then there is the impact of the utilization of the product itself. Here we might consider that since lithium from lithium-ion batteries has been poorly recycled, we accumulate a large number of end-of-life batteries in landfills, which can be hazardous to store, which could lead to water table contamination, and so on. Keep in mind that it is important to consider both the hazards and the *benefits* of chemistry. For example, the use of lithium-ion BEVs could be said to have a positive influence on planetary systems by reducing society's reliance on fossil fuel powered transportation, and so reducing anthropogenic emissions to the atmosphere, leading to fewer associated impacts on land (acid rain, extreme weather events) and aquatic (ocean acidification, eutrophication) subsystems.

Your SOCME should already be doing a fantastic job of representing the complex nature of how this one chemical process/product has an influence on the planetary environment. Perhaps the descriptions above the arrows and the seemingly interrelated influence on the ever-expanding use of a chemical process/product may lead you to now make a judgement on the *sustainability* of a particular chemical/process product. Look again at Figure 4.8. It is hardly an exhaustive representation of all components of the "lithium" system, but would you be prepared, based on your SOCME, to make a judgment about whether producing lithium (for use in BEVs) is *sustainable*? If so, why? If not, why not? Or... do we not have enough information to answer this question yet? What other information would we need?

And so *here* is where the human-level considerations could be introduced. **Stage 4** brings in other considerations that need to be addressed to better understand the overarching sustainability question. Whereas mapping out the land, aquatic and atmosphere subsystems visualized the *environmental* considerations related to sustainability, what of the economical, ethical, political, and social considerations? A nearly inexhaustive list of questions exists that you could ask at this point, but as a scaffold, a student could start with the prompting questions in Box 4.7. These questions collectively interrogate to *whose benefit* is the chemical process/product, and who has or does not have a say in how this chemical process/product is implemented in society.^{78,93}

The last two questions in Box 4.7 directly address human security and multi-species security, respectively.⁷⁵ Both of these feel *far* removed from the learning intentions of a standard chemistry classroom; but without attempting to holistically address these, we could not possibly hope to represent the true sustainability of a chemical process or product.

Figures 4.9 (social and political) and 4.10 (ethical and environmental) bring more subsystems together into the SOCME representation. Note how the addition of the human-level subsystems can make it easier to visualize

Box 4.7 Prompts for students to consider when building human-level subsystems (social, economic, ethical, political) of a SOCME (Stage 4).

The questions asked here would vary depending on if you are considering a “traditional”, large-scale, ubiquitous chemical process/product (for instance, fertilizers produced from the Haber–Bosch process) or perhaps an “innovative”, greener alternative (for instance, fertilizers produced using green hydrogen).

If it is already a large-scale ubiquitous chemical process:

- What economic reasons keep it going? Inexpensive? Easier to source feedstocks? Employment of citizens?
- Do these economic reasons hinder or fuel a political will for change?
- Is this chemical process maintaining or derailing political or social efforts to improve social equity?

Or, if it is an innovative, greener, yet-to-be fully implemented chemical process:

- What are some of the economic reasons that are slowing its broader implementation?
- What fuels the political will (if any) to implement this alternative?
- How would implementing this change the nature of society? Would it increase or decrease social equity?

Whatever chemical process or product you are examining, it is important to consider how that process or product is affected by or impacts humans. For example, consider who stands to benefit (or not benefit), and who has a voice (or does not have a voice) in how this chemical process or product is implemented:

- Who decides how this chemical product/process is implemented? Are these decisions made equitably across local and global societies? From what worldview was this decision made?
- Who stands to benefit from this chemical process/product? Who stands to *not* benefit, or what consequences do others face who do not have a voice in this decision?
- How does this chemical product/process impact human health? Does it provide a “human right” to live a life of dignity and free from want? Free from fear?
- How does this chemical product/process impact the lives of *other species* that inhabit the planet? Are decisions that we make as a human society ethical and equitable for other species who had no say or voice in these decisions?

For further inspiration, you may like to consider the questions developed by Ulrich, which provide a framework for critical reflection on decisions that impact society, taking into account issues such as motivation, power, knowledge and legitimacy.⁹³

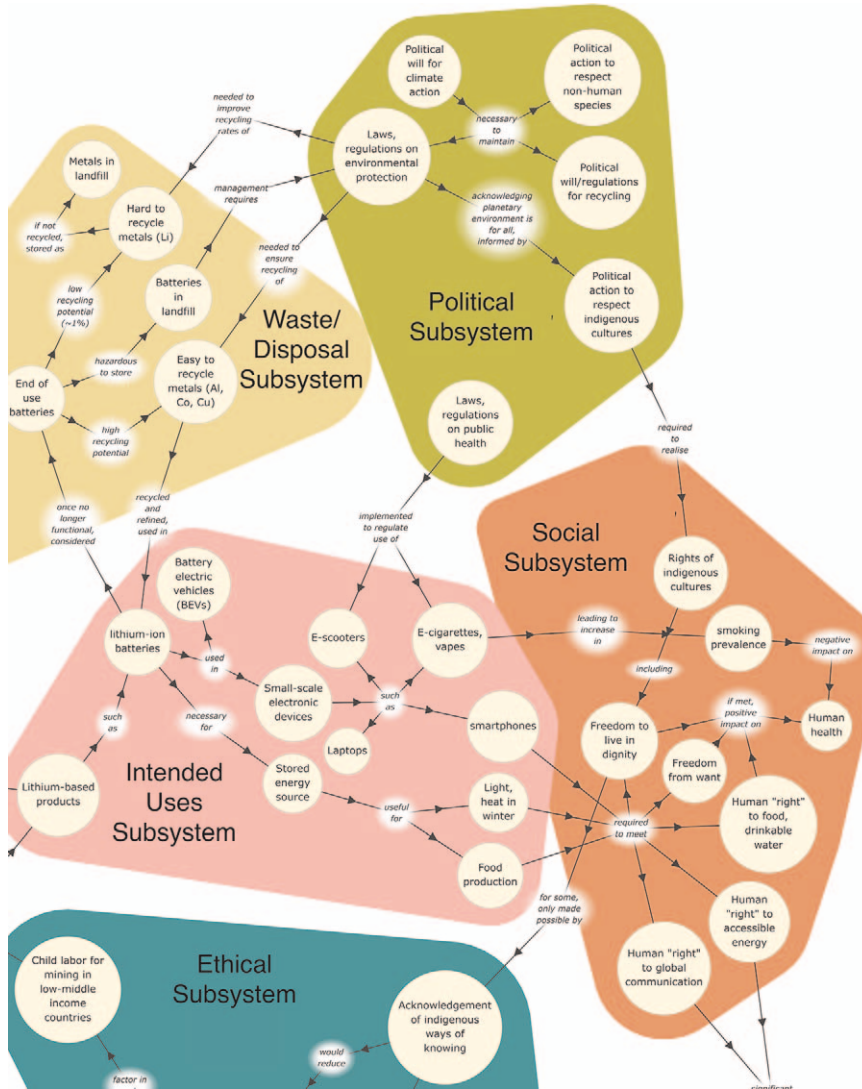


Figure 4.9 A further expanded SOCME, showing the interconnectedness of the political and social subsystems with other subsystems.

potential “big-picture” impacts of the chemical process or product on the other subsystems. Expanding on just a few of these new relationships, consider the following human-level subsystems for the lithium-ion battery context:

- **Ethical:** The enormous expansion of land and water extraction needed to source lithium for batteries will take place in mostly low- and middle-income countries (LMIC), or on ancestral lands of indigenous communities, with any benefits flowing not to these communities but to societies in high-income countries. Communities in these areas find

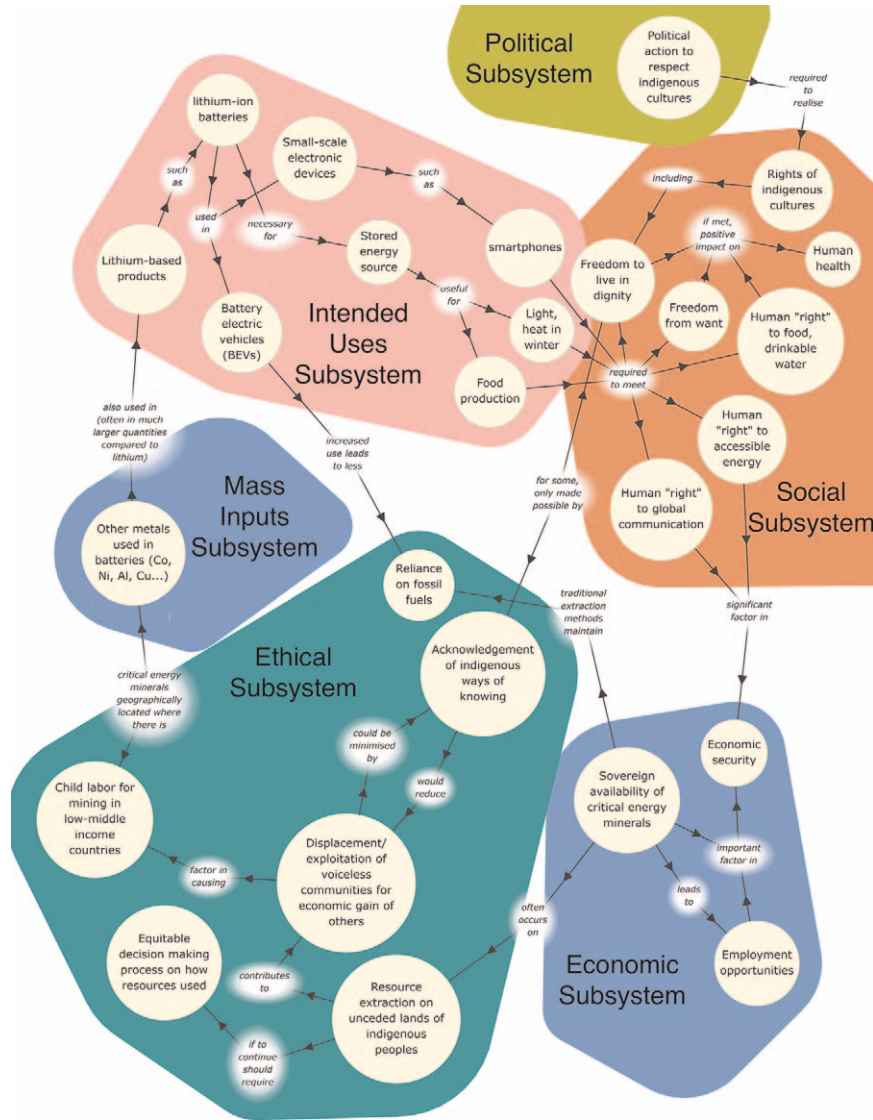


Figure 4.10 A further expanded SOCME, showing the interconnectedness of the ethical and economic subsystems with other subsystems.

themselves fighting for already limited amounts of water and energy that are instead used for mineral extraction.⁹⁴

- **Social:** Modern innovations in lithium-ion battery technology have made small-scale electronic devices like e-cigarettes (vapes) cheap and affordable. But this market has also been largely unregulated, which has led to a massive increase in smoking prevalence in youths after decades of decline, which will have long-term impacts on human health.⁹⁵

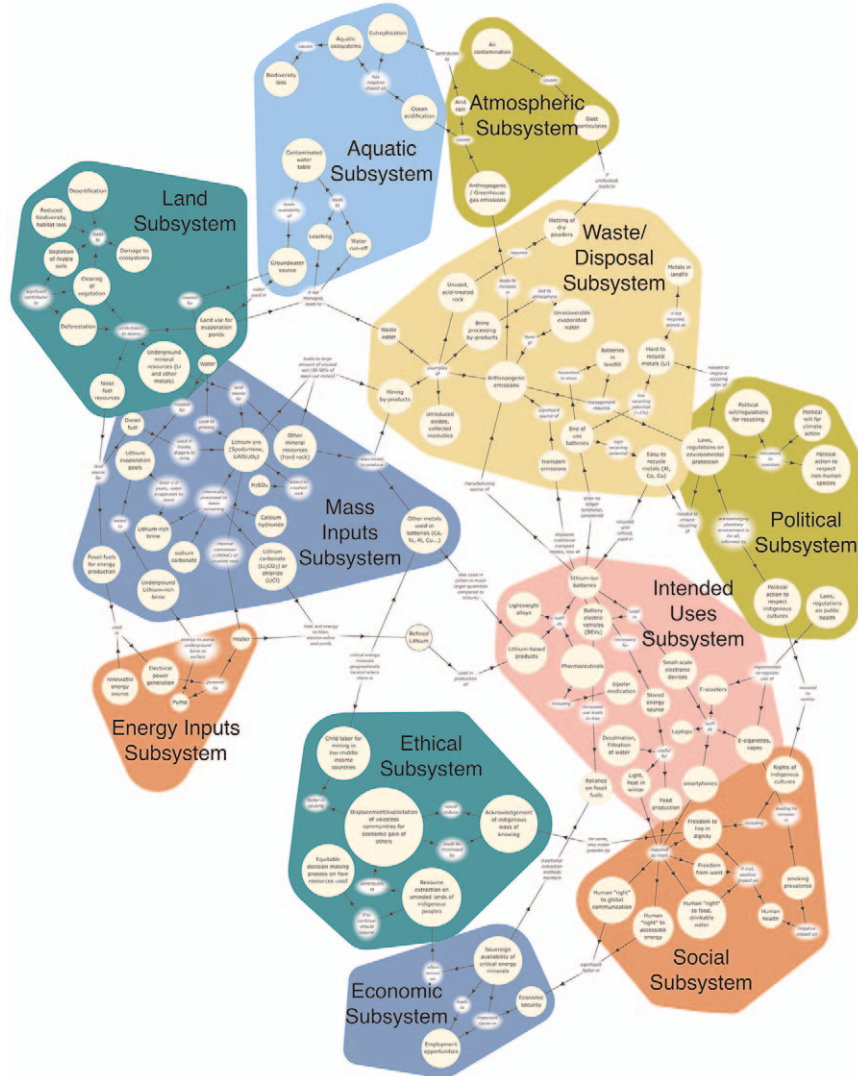


Figure 4.11 The completed SOCME, for lithium use in the green energy transition.

- **Political:** Increasing public pressure on governments to take meaningful steps to address climate action has led to new laws and regulations that set high mandates for recycling rates of materials from batteries, increasing recovery rates of lithium and other metals, reducing the need for more mines and brine processing.⁸⁶
- **Economic:** The availability of critical minerals, including lithium, brings with it economic security and employment opportunities to countries like Australia and Chile, but also leaves them vulnerable to volatile market prices and foreign companies moving profits overseas, leaving these governments unable to budget for long-term social expenditure.⁹⁶

If we were to *now* attempt to answer the question “is this chemical process or product sustainable?” we could be more confident that we would have considered not just the science, but also the broader social science reasons related to sustainability. Although it is very detailed, Figure 4.11 does not attempt to represent the “lithium” issue in its entirety (we would need another whole chapter for this!). Another benefit of investigating the “sustainable” question with your for-now-finished SOCME, is that if you answered “no”, the SOCME gives you insight into the complex nature of this overall system, and so gives you avenues to explore what could possibly be done to address this lack of sustainability. Box 4.8 provides one final list of post-SOCME questions to explore this further.

Box 4.8 Prompts for students to consider when addressing the sustainability of a system as represented in a SOCME.

Sustainability can be considered an *emergent property* of the overall system.⁷² Consider your full SOCME:

- Does the chemical process/product at the core of your SOCME appear “sustainable”?
 - with respect to the planetary boundaries?
 - with respect to society’s needs, or the right for all humans (and other species) to live in dignity, free from fear and want?

It is likely that your answer is... no. If so, does your SOCME provide some insight as to what could be done about it? Interrogate the nature of connections formed both *within* and *across* subsystems:

- Could one or more steps in the core reaction be done differently, more sustainably?
 - A greener feedstock? A circular alternative to a linear one (see Chapter 1)?
- How would such a small change lead to updating other connections in the SOCME?
 - How would that small change shift the overall impact on planetary subsystems?
 - Would there be a shift in how the chemical process/product is used by humans?
 - Would this small change shift the economics of the chemical process/product?
 - Could the small change lead to a more equitable and just global society?

See your initial SOCME as a “snapshot”, and so consider the *temporal* nature of chemical knowledge and how greener changes to the underlying chemical process can have a significant positive influence on society and our planet, should there be the political will to implement it.

Repeating this activity with another class or group of students would also likely lead to different representations, as student input, influenced by their local environments, would largely define the shape and substance of the SOCME. With small groups of students in one class, the SOCMEs from each group would have significant similarities and differences, which could then provide the impetus for further classroom debate and discussion. We have no doubt that the activity repeated the following year would also have significant differences from the previous year's activity. As a consequence, year upon year, the activity of building a SOCME allows not only students, but us to learn more about the topic and contexts ourselves.

4.5 Closing Thoughts

Let us say that, after reading this chapter, you are convinced you want to integrate aspects of systems thinking into your chemistry courses. Where do you start? A good first step would be to look at some existing resources. Because systems thinking is relatively new to the chemistry education community, resources are limited but are developing over time. For example, the December 2019 special issue of the *Journal of Chemical Education* focused on systems thinking.⁹⁷ The articles in that issue provide a basic background of systems thinking, as well as some ideas for classroom implementation of systems thinking.

The American Chemical Society's Green Chemistry Institute has been supporting educators in the development of systems thinking modules for use in chemistry courses. As each module is developed, it will be posted on a common website. At the time of this printing, there is a module that can be used to introduce students to systems thinking concepts, with specific ties to green chemistry and sustainability-related concepts ("Introduction to Systems Thinking in Chemistry").⁹⁸ There is also a module that guides students to construct a SOCME as they explore ideal gas concepts in the context of the anthropogenic nitrogen cycle ("Anthropogenic N₂ Cycle: Gas Phase Reactions Essential to Food and Life").⁹⁹

Finally, the International Union of Pure and Applied Chemistry has sponsored the development of a website—Sustainability and Systems Thinking in Chemistry Education—that will act as a central location for resources related to the implementation of systems thinking in a chemistry education context.¹⁰⁰

But what if none of these pre-existing resources meet the needs of your classroom and your students? You can still use some of the recommendations from this chapter to iteratively add aspects of systems thinking to your classroom practice, whether that be through the integration of SOCMEs or tasks that address the cognitive skills listed in the ChEMIST table. Before you do that though, we suggest you identify chemistry content and a corresponding context that are appropriate for a systems thinking approach.

There are many different pedagogies that can be used to help students develop understandings of chemical concepts. It is unreasonable to believe

that any one pedagogy, even systems thinking, would be ideal for teaching *all* chemical concepts or for *all* teaching purposes.^{35,101} So, which types of chemistry content would be better for a systems thinking approach? Richmond and Goodman note that as systems thinking is concerned with changes in behaviors over time, it would be most useful to employ systems thinking to examine problems or phenomena that unfold over time or have a time/dynamic dimension to them.^{34,102} For example, the following topics might be appropriate for a systems thinking approach, although this list is certainly not exhaustive: gas laws/gas behavior, self-assembly, equilibrium, crystal structure/crystal formation, bond formation, and precipitation reactions/solubility.

When it comes to choosing an appropriate context, Draper and Forrester suggest that students should participate in systems thinking about topics that are of interest to them.^{33,103} You know your students. Make sure that their engagement in a systems thinking approach is contextualized in a topic that will make them want to learn more. If you are stuck for appropriate contexts, try contextualizing chemistry concepts in the United Nations Sustainable Development Goals. We need future global citizens who are aware of and can use their chemistry knowledge to address these goals and improve the world around them!

Once you have content and a context that are appropriate, we repeat that changing to a systems thinking approach should not happen all at once. In fact, we asked instructors who are currently using systems thinking to give advice to others who are thinking about using the approach in their classrooms. The very first thing they said was **START SMALL!** Look at what you are doing in your course right now. Maybe you are already doing some things that are systems thinking oriented and you just need to expand on what you are doing. Then, when you are ready to make changes, start small. Do not make major changes all at once. Plan on this being an iterative process; it will take time. Collaborate with others within and beyond your discipline so you can bring in interdisciplinary perspectives and applications related to planetary sustainability. Be patient, positive, and flexible...with yourself...with your students...with the process. But, most importantly, **JUST TRY IT!**

Online Resources

Full size high-resolution versions of Figures 4.6–4.11 are available online at <https://doi.org/10.1039/9781837676576>, and can be accessed *via* the QR code below.



References

1. P. G. Mahaffy, E. J. Brush, J. A. Haack and F. M. Ho, *J. Chem. Educ.*, 2019, **96**, 2679.
2. United Nations Sustainable Development Goals: The 17 Goals, <https://sdgs.un.org/goals> (accessed August 2025).
3. D. J. C. Constable, C. Jimenez-Gonzalez and S. A. Matlin, *J. Chem. Educ.*, 2019, **96**, 2689.
4. M. Orgill, S. York and J. MacKellar, *J. Chem. Educ.*, 2019, **96**, 2720.
5. V. Talanquer, R. Bucat, R. Tasker and P. G. Mahaffy, *J. Chem. Educ.*, 2020, **97**, 2696.
6. S. York, R. Lavi, Y. J. Dori and M. Orgill, *J. Chem. Educ.*, 2019, **96**, 2742–2751.
7. S. York and M. Orgill, *J. Chem. Educ.*, 2020, **97**, 2114–2129.
8. Systems Thinking in Chemistry for Sustainability: Towards 2030 and beyond (STCS 2030+), <https://iupac.org/project/2020-014-3-050/> (accessed August 2025).
9. D. Hammond, *tripleC*, 2005, **3**, 20.
10. S. Delaney, J. P. Ferguson and M. Schultz, *Int. J. Sci. Educ.*, 2021, **43**, 2618.
11. A. Jackson and G. A. Hurst, *Chem. Educ. Res. Pract.*, 2021, **22**, 855.
12. S. A. Matlin, G. Mehta, H. Hopf and A. Krief, *Nat. Chem.*, 2016, **8**, 393.
13. M. Schultz, J. Lai, J. P. Ferguson and S. Delaney, *J. Chem. Educ.*, 2021, **98**, 3100.
14. A. R. Szozda, K. Bruyere, H. Lee, P. G. Mahaffy and A. B. Flynn, *J. Chem. Educ.*, 2022, **99**, 2474.
15. S. York and M. Orgill, *J. Chem. Educ.*, 2024, **101**, 10.
16. N. H. Sabelli, *J. Learn. Sci.*, 2006, **15**, 5.
17. J. Tripto, O. B. Z. Assaraf, Z. Snipir and M. Amit, *Instr. Sci.*, 2017, **45**, 73.
18. D. M. Fisher, *Syst. Dyn. Rev.*, 2011, **27**, 394.
19. D. M. Fisher, *Systems*, 2018, **6**, 1.
20. C. E. Hmelo, D. L. Holton and J. L. Kolodner, *J. Learn. Sci.*, 2000, **9**, 247.
21. Y. Kali, N. Orion and B.-S. Eylon, *J. Res. Sci. Teach.*, 2003, **40**, 545.
22. D. A. Lyneis, Bringing System Dynamics to a School Near You: Suggestions for Introducing and Sustaining System Dynamics in K-12 Education, <http://static.clexchange.org/ftp/documents/implementation/IM2013BringSDToSchool.pdf> (accessed August 2025).
23. E. B. Mandinach and H. F. Cline, *Syst. Dyn. Rev.*, 1993, **9**, 195.
24. L. G. Mathews and A. Jones, *Issues Int. Stud.*, 2008, **26**, 73.
25. R. P. Verhoeff, A. J. Waarlo and K. T. Boersma, *Int. J. Sci. Educ.*, 2008, **30**, 543.
26. S. A. Yoon, S.-E. Goh and M. Park, *Rev. Educ. Res.*, 2018, **88**, 285.
27. L. B. Sweeney, Creative Learning Exchange Newsletter, 2005, vol. 14, <http://static.clexchange.org/ftp/documents/Research/RS2005-09Homology.pdf> (accessed August 2025).
28. C. E. Hmelo-Silver, R. Jordan, C. Eberbach and S. Sinha, *Instr. Sci.*, 2017, **45**, 53.

29. R. P. Verhoeff, M.-C. P. J. Knippels, M. G. R. Gilissen and K. T. Boersma, *Front. Educ.*, 2018, **3**, 1.
30. R. Zaraza, *Curric. Tech. Q.*, 1995, **5**, 1.
31. R. D. Arnold and J. P. Wade, *Procedia Comput. Sci.*, 2015, **44**, 669.
32. L. B. Sweeney, *Solutions J.*, 2012, **3**, 55, <https://www.utne.com/mind-and-body/learning-to-connect-the-dots/> (accessed August 2025).
33. J. W. Forrester, *Syst. Dyn. Rev.*, 2016, **32**, 187.
34. M. Goodman, *Syst. Thinker*, 1997, **8**, 6, <https://thesystemsthinker.com/systems-thinking-what-why-when-where-and-how/> (accessed August 2025).
35. D. H. Kim, *Introduction to Systems Thinking*, Pegasus Communications, Waltham, MA, 1999.
36. G. Ossimitz, *Teaching System Dynamics and Systems Thinking in Austria and Germany*, <https://proceedings.systemdynamics.org/2000/PDFs/ossimitz.pdf> (accessed August 2025).
37. B. Richmond, *Syst. Dyn. Rev.*, 1993, **9**, 113.
38. B. Richmond, *Syst. Dyn. Rev.*, 1994, **10**, 135.
39. A. Roychoudhury, D. P. Shepardson, A. Hirsch, D. Niyogi, J. Mehta and S. Top, *Sci. Educ.*, 2017, **25**, 73.
40. N. P. Sheehy, J. W. Wylie, C. McGuinness and G. Orchard, *Environ. Educ. Res.*, 2000, **6**, 109.
41. M. Evagorou, K. Korfiatis, C. Nicolaou and C. Constantinou, *Int. J. Sci. Educ.*, 2009, **31**, 655–674.
42. L. B. Sweeney and J. D. Sterman, *Syst. Dyn. Rev.*, 2000, **16**, 249.
43. O. B.-Z. Assaraf and N. Orion, *J. Res. Sci. Teach.*, 2005, **42**, 518.
44. J. R. Kirby, in *Learning Strategies and Learning Styles*, ed. R. R. Schmeck, Springer Science+Business Media, 1988, ch. 9, pp. 229–274.
45. F. Marton, in *Learning Strategies and Learning Styles*, ed. R. R. Schmeck, Springer Science+Business Media, 1988, ch. 3, pp. 53–82.
46. R. R. Schmeck, in *Learning Strategies and Learning Styles*, ed. R. R. Schmeck, Springer Science+Business Media, 1988, ch. 1, pp. 3–19.
47. R. R. Schmeck, in *Learning Strategies and Learning Styles*, ed. R. R. Schmeck, Springer Science+Business Media, 1988, ch. 12, pp. 317–347.
48. O. De Jong, *Chem. Educ. Int.*, 2008, **8**, 1.
49. J. K. Gilbert, *Int. J. Sci. Educ.*, 2006, **28**, 957.
50. J. K. Gilbert, in *Debates in Science Education*, ed. M. Watts, Routledge, New York, 2014, ch. 11, pp. 145–157.
51. T. Overton, *New Dir. Teach. Phys. Sci.*, 2007, **3**, 7.
52. T. L. Overton, B. Byers and M. K. Seery, in *Innovative Methods in Teaching and Learning Chemistry in Higher Education*, ed. I. Eilks and B. Byers, Royal Society of Chemistry, Cambridge, 2009, ch. 3, pp. 43–60.
53. VC3Chem Acids and Bases lesson, https://vc3chem.com/acidsBases/A_intro_1.html (accessed August 2025).
54. A. Brunning, Ocean Acidification: “The Other Carbon Dioxide Problem”, <https://www.compoundchem.com/2017/01/18/ocean-acidification-co2/> (accessed August 2025).

55. S. C. Doney, V. J. Fabry, R. A. Felly and J. A. Kleypas, *Annu. Rev. Mar. Sci.*, 2009, **1**, 169.
56. J. P. Gattuso, P. G. Brewer, O. Hoegh-Guldberg, J. A. Kleypas, H. O. Pörtner and D. N. Schmidt, Cross-chapter box on ocean acidification, <https://core.ac.uk/download/pdf/42904806.pdf> (accessed August 2025).
57. K. J. Kroeker, R. L. Kordas, R. Crim, I. E. Hendriks, L. Ramajo, G. S. Singh, C. M. Duarte and J. P. Gattuso, *Global Change Biol.*, 2013, **19**, 1884.
58. Acidic Oceans May be a Boon for Some Marine Dwellers, <https://www.science.org/content/article/acidic-oceans-may-be-boon-some-marine-dwellers> (accessed August 2025).
59. E. L. Cross, E. M. Harper and L. S. Peck, *Environ. Sci. Technol.*, 2019, **53**, 5016.
60. M. J. Hardt and C. Sfina, How Acidification Threatens Oceans from the Inside Out, <https://www.scientificamerican.com/article/threatening-ocean-life/> (accessed August 2025).
61. A. J. Tasoff and D. W. Johnson, *Evol. Appl.*, 2019, **12**, 560.
62. D. L. Dixson, P. L. Munday and G. P. Jones, *Ecol. Lett.*, 2010, **13**, 68.
63. C. Harvey and E&E News, Some Crabs Are Losing Their Sense of Smell as Oceans Acidify, <https://www.scientificamerican.com/article/some-crabs-are-losing-their-sense-of-smell-as-oceans-acidify/#:~:text=Numerous%20studies%20have%20found%20that,important%20odors%20in%20the%20water> (accessed August 2025).
64. U. Riebesell, N. Aberle-Malzahn, E. P. Achterberg, M. Alueró-Muñiz, S. Alvarez-Fernandez, J. Arístegui, L. T. Bach, M. Boersma, T. Boxhammer, W. Guan, M. Haunost, H. G. Horn, C. R. Löscher, A. Ludwig, C. Spisla, M. Sswat, P. Stange and J. Taucher, *Nat. Clim. Change*, 2018, **8**, 1082.
65. L. J. Falkenberg, R. G. J. Bellerby, S. D. Connell, L. E. Fleming, B. Maycock, B. D. Russell, F. J. Sullivan and S. Dupont, *Int. J. Environ. Res. Public Health*, 2020, **17**, 1.
66. United Nations Sustainable Development Goal 14, <https://www.un.org/sustainabledevelopment/oceans/> (accessed August 2025).
67. SOCKit, <https://applets.kcvs.ca/socket/> (accessed August 2025).
68. M. Schultz, D. Chan, A. C. Eaton, J. P. Ferguson, R. Houghton, A. Ramdzan and S. Delaney, *Educ. Sci.*, 2022, **12**, 596.
69. A. R. Szozda, P. G. Mahaffy and A. B. Flynn, *J. Chem. Educ.*, 2023, **100**, 1763.
70. S. A. Matlin, G. Mehta, S. E. Cornell, A. Krief and H. Hopf, *RSC Sustainability*, 2023, **1**, 1704.
71. K. B. Aubrecht, Y. J. Dori, T. A. Holme, R. Lavi, S. A. Matlin, M. Orgill and H. Skaza-Acosta, *J. Chem. Educ.*, 2019, **96**, 2888.
72. P. G. Mahaffy, S. A. Matlin, T. A. Holme and J. MacKellar, *Nat. Sustainable*, 2019, **2**, 362.
73. A. C. Eaton, S. Delaney and M. Schultz, *J. Chem. Educ.*, 2019, **96**, 2968.
74. B. Sauser and J. Boardman, in *Modeling and Simulation Support for System of Systems Engineering Applications*, ed. L. B. Rainey and A. Tolck, John Wiley & Sons, 2014, ch. 11, pp. 273–302.

75. S. A. Matlin, G. Mehta, H. Hopf, A. Krief, L. Keßler and K. Kümmerer, *Sustainable Chem. Pharm.*, 2020, **17**, 100312.
76. M. Reynders, L. A. Pilcher and M. Potgieter, *J. Chem. Educ.*, 2023, **100**, 1357.
77. P. G. Mahaffy, S. A. Matlin, J. M. Whalen and T. A. Holme, *J. Chem. Educ.*, 2019, **96**, 2730.
78. S. A. Matlin, A. Krief, H. Hopf and G. Mehta, *Angew. Chem., Int. Ed.*, 2021, **60**, 25610–25623.
79. US Department of Energy, Critical Materials Assessment, July 2023, https://www.energy.gov/sites/default/files/2023-07/doe-critical-material-assessment_07312023.pdf (accessed August 2025).
80. S. Bruce, B. Delaval, A. Moisi, J. Ford, I. West, J. Loh and J. Hayward, Critical Energy Minerals Roadmap, https://www.csiro.au/-/media/Do-Business/Files/Futures/Critical-energy-minerals-roadmap/21-00041_MR_REPORT_CriticalEnergyMineralsRoadmap_WEB_210420.pdf (accessed August 2025).
81. Talison Lithium Sustainability Overview, <https://www.talisonlithium.com/sustainability-overview> (accessed August 2025).
82. R. C. Berg and T. A. Sady-Kennedy, South America's Lithium Triangle: Opportunities for the Biden Administration, <https://www.csis.org/analysis/south-americas-lithium-triangle-opportunities-biden-administration> (accessed August 2025).
83. J. C. Kelly, M. Wang, Q. Dai and O. Winjobi, *Resour., Conserv. Recycl.*, 2021, **174**, 105762.
84. O. Murphy and M. N. Haji, *Front. Chem. Eng.*, 2022, **4**, 1008680.
85. US Department of Energy, National Blueprint for Lithium Batteries 2021-2030, <https://www.energy.gov/eere/vehicles/articles/national-blueprint-lithium-batteries> (accessed August 2025).
86. M. Jacoby, *C&E News*, 2019, **97**, 29.
87. G. Bhutada, The Key Minerals in an EV Battery, <https://elements.visualcapitalist.com/the-key-minerals-in-an-ev-battery/> (accessed August 2025).
88. M. Peplow, *C&E News*, 2023, **101**, 24.
89. Q. Wang, P. Ping, X. Zhao, G. Chu, J. Sun and C. Chen, *J. Power Sources*, 2012, **208**, 210.
90. B. Swain, *Sep. Purif. Technol.*, 2017, **172**, 388.
91. P. K. Nayak, L. Yang, W. Brehm and P. Adelhelm, *Angew. Chem., Int. Ed.*, 2018, **57**, 102.
92. T. Holme, *Sustainable Chem. Pharm.*, 2020, **16**, 100234.
93. W. Ulrich, A Brief Introduction to Critical Systems Heuristics (CSH), https://wulrich.com/downloads/ulrich_2005f.pdf (accessed August 2025).
94. H. Romero, M. Méndez and P. Smith, *Environ. Justice*, 2012, **5**, 70.
95. C. Watts, S. Egger, A. Dessaix, A. Brooks, E. Jenkinson, P. Grogan and B. Freeman, *Aust. N. Z. J. Public Health*, 2022, **46**, 814.
96. J. Barandiarán, *World Dev.*, 2019, **113**, 381.
97. Reimagining Chemistry Education: Systems Thinking and Green and Sustainable Chemistry (December 2019 special issue of the Journal of

- Chemical Education), <https://pubs.acs.org/toc/jceda8/96/12> (accessed August 2025).
98. ACS Green Chemistry Institute Introduction to Systems Thinking in Chemistry Module, <https://www.acs.org/green-chemistry-sustainability/education/teaching-modules/systems-thinking.html> (accessed August 2025).
 99. ACS Green Chemistry Institute The Anthropogenic N₂ Cycle: Gas Phase Reactions Essential to Food and Life module, <https://www.acs.org/green-chemistry-sustainability/education/teaching-modules/ideal-gases.html> (accessed August 2025).
 100. Sustainability and Systems Thinking in Chemistry Education (SaS-TiCE), <https://sastice.com> (accessed August 2025).
 101. R. L. Goldstone and U. Wilensky, *J. Learn. Sci.*, 2008, **17**, 465.
 102. B. Richmond, *Syst. Thinker*, 1997, **8**, 1.
 103. F. Draper, *Syst. Dyn. Rev.*, 1993, **9**, 207.

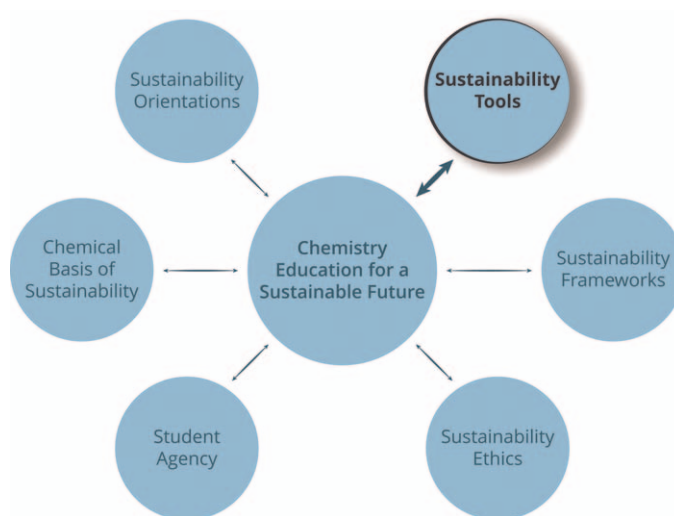
CHAPTER 5

Sustainability Tools II – Impact-based Metrics[†]

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5.1 Opening Thoughts

Which is greener, a reusable cotton shopping bag or a reusable polyethylene shopping bag? Ask any student, and they are likely to choose the cotton bag. This choice makes intuitive sense, because cotton is both renewable and biodegradable, along with the common misconception that anything “natural” must be benign. However, if we were to consider the question in terms of quantitative environmental impacts, we might come to a different conclusion. Compared to the polyethylene bag, the cotton bag causes 40 times more global warming, 90 times more acid rain, 100 times more smog, 70 times more human toxicity, 120 times more freshwater ecotoxicity, and 20 times more resource depletion!¹ Even in terms of fossil fuel consumption, reusable cotton bags are many times worse than reusable plastic bags.^{2,3} This example shows why we should be teaching students to consider quantitative impact metrics, not myths and generalizations, in their decisions about what is green or sustainable.

Shouldn't every science student learn how to consider chemistry's potential for harm along with its benefits and have the agency (see Chapter 9) to make informed decisions about chemistry? This ability is key to green decision-making in chemistry and related disciplines. Without this ability, students cannot put into action the goal of green chemistry, which is to reduce harm from chemicals to health and the environment. To discern whether modifications to a chemical process or product have reduced its environmental impact, one needs to be able to compare the old and new technology and decide which causes the least harm.

For many undergraduate students, their first-year chemistry course may be the end of their formal education in chemistry. With what tools do we leave them? Unfortunately, the standard method for quantifying harm, Life Cycle Assessment (LCA), is generally considered too complex and time-consuming to fit into either first-year undergraduate chemistry courses or, indeed, into any part of the required undergraduate chemistry curriculum. Instructors resist adding any complex content because to do so would require the removal of some existing content, which is anathema for most departments and instructors. Instead, overly simple mass-based metrics are taught, if any green chemistry is taught at all.

Here, we aim to rethink green chemistry education using a mindset of “quality over quantity,” in which the qualities of a chemical, for example, the potential for harm caused by waste, take precedence over quantity. The qualities are defined by **impact-based** metrics, while quantity refers to mass-based metrics. This chapter serves as a guide for the instructor who wishes to teach their chemistry students how to identify the least harmful of two or more options.

5.2 Background

5.2.1 What is Wrong with Mass-based Metrics?

The green chemistry metrics most commonly taught in undergraduate chemistry courses are atom economy (Box 5.1) and *E*-factor (Box 5.2), which

Box 5.1 Atom economy, one of the mass-based metrics.

$$\text{Atom economy} = \frac{\text{FW of desired product}}{\text{FW of all reagents}} \times 100\%$$

Includes:	Disregards:
- reagents	- side products
- products	- solvents, catalysts
- byproducts	- separation aids
	- energy consumption
	- synthesis of starting materials
	- harm of any kind

Box 5.2 *E*-factor, another of the mass-based metrics. The related metrics called process mass intensity and effective mass yield are equal to $E + 1$ and $1/(E + 1)$, respectively.

$$E \text{ factor} = \frac{\text{mass of waste}}{\text{mass of product}}$$

Includes:	Disregards:
- reagents	- synthesis of starting materials
- products	- energy consumption
- byproducts	- harm of any kind
- solvents, catalysts	
- separation aids	

are based solely on mass.⁴⁻⁶ They are used to evaluate reactions by considering the mass of reagents or waste compared to the mass of the desired product. However, they ignore the fact that some chemicals are more harmful than others. Mass-based metrics benefit from simplicity but are flawed because they give no measure of harm.

Mass-based metrics like *E*-factor and atom economy take little time for instructors to teach, are easy for students to calculate, and displace very little (if any) existing content. These mass-based metrics calculate, in one way or another, the mass of wasted materials and are taught under the assumption that a process that produces less waste must be greener. That assumption is incorrect. A process that produces little waste might use much more energy or might generate extremely harmful waste. In contrast, a process that produces more waste might use less energy or might generate nearly harmless waste.

Thus, mass-based metrics are not accurate indicators of environmental harm and are unreliable for determining which of two or more options is the least harmful.

Impact-based metrics offer advantages over mass-based metrics by enabling students to compare chemicals, reactions, or whole processes (see below: *Step 2. System Boundaries*) for their potential harm. However, due to the added variability and subjectivity compared to mass (*e.g.*, which impact should I care about?) and their use in complex life cycle assessments, impact-based metrics are widely perceived as too difficult for the early undergraduate curriculum. This chapter aims to show that this is not the case. It presents various approaches to introduce impact-based metrics in first-year or upper-level chemistry courses to enable students to identify the least harmful of two or more options.

5.2.2 An Introduction to Impact-based Metrics

In daily life, people are faced with decisions that require them to consider both an action and its potential consequences. For example, should one carry around a reusable coffee mug or use a disposable paper cup, and does the inconvenience of the former outweigh the impacts of the latter? In chemistry, we must similarly consider the benefits and hazards caused by reactions and processes.⁷ A simple way of evaluating a chemical process is by looking at how much waste it produces compared to how much of the desired product we get. Waste comes from solvents needed for the reaction, reagents that are not used up in the reaction, and by-products. One way or another, waste ends up being released into the environment. Let us consider an example:

Process A produces 10 kg of total waste for each 1 kg of product.

Process B produces 3 kg of total waste for each 1 kg of product.

Which process is better? Process B produces and likely releases less waste into the environment, so it looks like the best choice. But WAIT! We cannot know for sure, since all waste is not equal. We need to know both the mass of the chemical waste and its potential for harm to determine its **impact**, which is a measure of harm. Let us reconsider the example with more information:

The waste produced by Process A is CO₂.

The waste produced by Process B is CH₄ (methane).

To know which process causes less harm, one must consider the impact of releasing 10 kg of CO₂ into the environment compared to 3 kg of CH₄. As greenhouse gases, both contribute to global warming, but 3 kg of CH₄ would have a greater warming effect. Thus, it is insufficient to consider only the mass of waste.

The harm caused by each chemical released into the environment is quantified by the generic equation shown in Box 5.3. The potential, *P*, quantifies how much harm the chemical causes compared to an equal mass of a reference

Box 5.3 The equation and mathematical basis of both impact-based metrics and LCA.

$$I = P \cdot m$$

where I = impact (a measure of harm)

P = potential of the chemical to cause harm

m = mass of the chemical released into the environment

compound. When P is multiplied by m , the mass of chemical released, the product is the impact, I , which is the harm caused to the environment.

The value of P depends on the type of harm, and there are many to consider: global warming, human toxicity, ecotoxicity, acidification (acid rain formation) potential, *etc.* For example, methane has a global warming potential (P_{GW}) of 28 and an acidification potential (P_{A}) of zero. Methane thus contributes to global warming but not to acidification. To demonstrate how impact is determined, we will calculate the global warming harm caused by releasing 3 kg CH_4 . As mentioned earlier, the global warming potential (P_{GW}) for methane is 28, which means a kg of methane would cause 28 times as much global warming as a kg of the reference compound, carbon dioxide. The P_{GW} value has units of “kg of CO_2 equivalents per kg of methane,” but it is often simplified by stating that P_{GW} is unitless. Given that the mass of methane released is 3 kg, the global warming impact (I_{GW}) caused by this release can be calculated:

$$\begin{aligned} \text{Global warming impact } (I_{\text{GW}}) &= P_{\text{GW}} \cdot m = 28 \times 3 \text{ kg} \\ &= 84 \text{ kg of } \text{CO}_2 \text{ equivalents} \end{aligned}$$

or, to be more explicit with the units, we could write it as follows:

$$I_{\text{GW}} = P_{\text{GW}} \cdot m = 28 \text{ kg } \text{CO}_2 \text{ equivalents/kg} \times 3 \text{ kg} = 84 \text{ kg of } \text{CO}_2 \text{ equivalents}$$

Since P_{GW} for CO_2 is 1, the global warming impact in process A is 10 kg of CO_2 equivalents, considerably less than the 84 kg of CO_2 equivalents for process B. This simple example demonstrates that both the quantity and type of waste produced in a chemical process are needed to determine which one causes less harm.

The same calculation can quantify other types of harm, such as acidification (acid rain formation), ecotoxicity, eutrophication (overfertilization), and others. Table 5.1 lists the types of potentials, their reference chemicals, and the typical units for the impact.

One impact, resource depletion, is calculated differently. The concern is not the emission of pollutants but rather the consumption of resources. Therefore, the equation is modified to use the mass of the chemical consumed rather than released (Box 5.4).

For example, imagine a process that uses 12 g of PtCl_2 (of which 73% or 8.8 g is Pt and 27% or 3.2 g is Cl), and none is recovered afterwards. The m_{RD} of that usage is 8.8 g for the Pt and 3.2 g for the Cl. The depletion potentials

Table 5.1 Common potentials, their standard reference chemicals, and impact units.

Potential	Reference chemical	Typical units for impact
Acidification	Sulfur dioxide	kg SO ₂ equivalents
Ecotoxicity	1,4-Dichlorobenzene (DCB)	kg 1,4-DCB equivalents
Eutrophication	Phosphorus or phosphate	kg PO ₄ equivalents
Global warming	Carbon dioxide	kg CO ₂ equivalents
Ozone depletion	CFC-11	kg CFC-11 equivalents
Particulates	Particles smaller than 2.5 μm	kg PM _{2.5} equivalents
Resource depletion	Antimony (Sb)	kg Sb equivalents
Photochemical ozone	Ethylene	kg C ₂ H ₄ equivalents
Toxicity	1,4-Dichlorobenzene	kg 1,4-DCB equivalents

Box 5.4 The equation for the calculation of resource depletion.

$$I_{\text{RD}} = P_{\text{RD}} \cdot m_{\text{RD}}$$

where I_{RD} = impact in terms of resource depletion

P_{RD} = depletion potential

m_{RD} = mass of the resource consumed

for Pt ($P_{\text{RD}} = 1.29$) and Cl ($P_{\text{RD}} = 4.9 \times 10^{-8}$) can be supplied to the students from the *Handbook on Life Cycle Assessment*.⁸ The formal units are kg of Sb equivalents per kg of element consumed, but depletion potentials can also be treated as unitless. The depletion impact is calculated:

$$\begin{aligned} \text{Resource depletion impact} &= I_{\text{RD}} = (1.29 \times 8.8 \text{ g}) + (4.9 \times 10^{-8} \times 3.2 \text{ g}) \\ &= 11.4 \text{ g Sb equivalents} \end{aligned}$$

It is reasonable and recommended that students neglect highly abundant elements (Al, Ar, Ba, C, Ca, Ce, Cl, Fe, H, K, Mg, N, Na, O, Rb, Sc, Si, Ti) in such calculations because, as seen in the above example, they effectively make no difference to the total depletion. This simplifies the math:

$$\text{Resource depletion impact} = I_{\text{RD}} \approx 1.29 \times 8.8 \text{ g} = 11.4 \text{ g Sb equivalents}$$

Calculations of the types shown in Boxes 5.3 and 5.4 can introduce impact-based metrics to students and replace or supplement the mass-based metrics more commonly used in introductions to green or sustainable chemistry. We published a teacher's resource (open access from 2025) explaining these metrics and how to find or calculate the potentials.⁹

5.2.3 Life Cycle Assessment

Life Cycle Assessment (LCA) uses impact-based metrics to evaluate entire processes for their potential for harm and thus is famous for being a

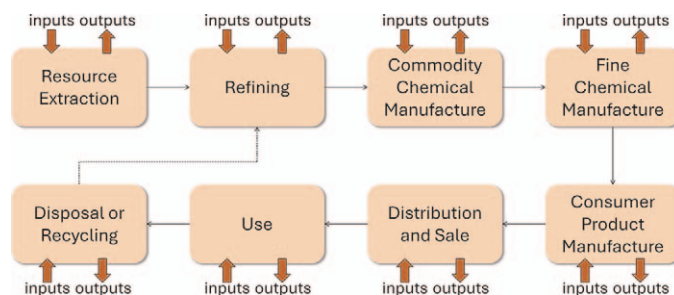


Figure 5.1 The standard type of LCA, called cradle-to-grave, considers the inputs and outputs of every step in the life cycle of a product, but a cradle-to-gate LCA only considers up to the end of the manufacturing of the chemical or consumer product. A gate-to-gate LCA, which is not generally practiced but is recommended here because it makes a student exercise much shorter, involves only the life stage in which the product is made. This figure contains original artwork.

time-consuming endeavor. Life Cycle Assessment takes into account the mass of all chemicals released into the environment and, importantly, considers the potential of each to cause harm. The entire assessment becomes complicated by considering the variety of impacts (toxicity, smog, global warming) and needing to make assumptions about how much of each chemical is released into the environment.

Fortunately, adopting impact-based metrics used for LCA into the high school or undergraduate curriculum is entirely feasible. While this helps build skills to conduct more complex assessments useful in the upper-year chemistry or chemical engineering curriculum, no further knowledge of LCA is needed on the part of the instructor or the students. Nevertheless, we provide a review of the general process here so that the role of impact-based metrics in environmental evaluations of chemical processes is clear.

The full process of Life Cycle Assessment consists of six steps:

Step 1. Goal and functional unit: let us suppose we are considering four syntheses of chemical X, called Processes #1, 2, 3, and 4. Our goal is to find out which of these four options causes the least harm. We then decide upon a functional unit, which is the requirement that all options must achieve. For example, let's say that the functional unit is the synthesis of 1 kg of chemical X.

Step 2. System boundaries: a standard LCA is a "cradle-to-grave" LCA, meaning it considers every stage in a product's life, from mining or farming the raw materials all the way to recycling, landfill, incineration, or disposal of the used product (Figure 5.1). Sometimes, a "cradle-to-gate" LCA is more appropriate, such as when comparing four syntheses of chemical X (top half of Figure 5.1). Any harm caused by the subsequent sale, use, and disposal of chemical X will be the same regardless of which synthesis we choose. In this kind of situation, those

later stages of the product's life can be ignored because they will have no effect on which route is the greenest.

Step 3. Inventory: every stage has inputs such as raw materials and energy and outputs such as pollution emissions and waste. The inventory is a complete list of all chemicals that are inputs and/or outputs, including the amounts used, produced, and emitted. This step is the most time-consuming. For a classroom activity or course assignment, it is important to design the assignment in a way that minimizes the time required for students to develop the inventory.

Step 4. Impact assessment: the various impacts (global warming, smog formation, *etc.*) of each emitted chemical are calculated by multiplying the potential by the mass emitted (Box 5.3). Once the impacts for all the chemicals in the inventory have been calculated, they are summed to provide a total impact for the process. For example, the total global warming impact is obtained as follows:

Total global warming

$$= I_{\text{GW}}(\text{chemical 1}) + I_{\text{GW}}(\text{chemical 2}) + \dots I_{\text{GW}}(\text{chemical } n)$$

Similarly, the total acidification, total smog formation, and other impacts are calculated. The totals are then tabulated and compared for each of the available options. The results of our hypothetical chemical X, which can be made by four processes, are shown in Table 5.2. Colors (or bold and italic emphasis) can be used to guide the eye to high and low impacts but are not required.

As Table 5.2 shows, a thorough LCA evaluates many impacts to avoid *risk migration*. Risk migration, also known as “regrettable substitution,” is the replacement of an old method or technology that poses a certain risk with a new one that poses a different risk. For example, the old technology might use lots of energy and therefore contribute greatly to global warming, while the new technology uses very little energy but causes high freshwater ecotoxicity. An LCA that only evaluated global warming would incorrectly lead one to believe that the new technology is wonderfully

Table 5.2 Environmental impact of four different processes for producing 1 kg of chemical X.

Process	Impacts (I) ^a					
	I_{AP}	I_{POC}	I_{GW}	I_{EU}	I_{HT}	I_{AD}
#1	0.3	10	3000	0.3	3000	0.1
#2	2	60	20 000	0.02	4000	0.3
#3	<i>5×10^{-6}</i>	<i>1</i>	<i>0.05</i>	<i>5×10^{-8}</i>	100 000	<i>0.0005</i>
#4	0.7	20	6000	0.007	<i>800</i>	0.007
Units ^b	kg SO ₂ eq	kg C ₂ H ₄ eq	kg CO ₂ eq	kg PO ₄ eq	kg DCB eq	kg Sb eq

^a AP: acidification potential, POC: photochemical ozone (smog) creation, GW: global warming, EU: eutrophication, HT: human toxicity, AD: abiotic depletion.

^b Units are all in the format kilograms of [reference chemical] equivalents. DCB: 1,4-dichlorobenzene.

green. An LCA that includes many impacts, including freshwater ecotoxicity, would make the flaws in the new technology abundantly clear. Because the greatest workload in an LCA is associated with the Inventory Step #3, not the Impact Assessment Step #4, doubling the number of calculated impacts does not double the total workload.

Step 5. Interpretation: we can now choose which of the options is the greenest. For each impact, compare numbers within the column. The smaller the value, the better. Negative numbers are wonderful but rare. In Table 5.2, we see that the greenest options are probably processes #3 and 4. Process #3 is the greenest option for global warming but is the worst option for human toxicity. Process #4 is very green for human toxicity but worse than #3 in all other respects.

To pick a winner, we have to make a trade-off. For example, if we believe global warming to be the most important impact, then we could choose synthesis #3 and be willing to live with the fact that it is going to cause more human toxicity. When faced with a problem like this, student teams intuitively grasp the concept of trade-offs and explain their decision in such terms.

Since the impact metrics have different units, do not compare numbers in different columns. For example, a student might be tempted to say that a human toxicity of 100 000 kg DCB eq is worse than a global warming of 6000 kg CO₂ eq. It might look that way because the number is bigger, but it is not a fair comparison because they have different units. It is like saying that 5 minutes is bigger than 1 meter. Similarly, never total up the numbers in a row (*e.g.* 0.3 + 10 + 3000 + *etc.*). As any good chemistry student will tell you, one should not add numbers with different units. It would be analogous to calculating the sum of 1 meter plus 5 minutes.

Another important part of the interpretation step is identifying and considering impacts that are not included in the LCA. Does one of the processes use a flammable or explosive substance? Do they use renewable or non-renewable feedstocks? While the LCA may not have quantified those impacts, they can still be a part of the decision-making process.

Step 6. Sensitivity analysis: this final step may not be part of a short undergraduate exercise, but it is important for anyone who wants to understand LCAs. The process of doing an LCA involves making many assumptions. For example, we could assume that the chromatographic purification of the crude product requires 20 g of silica. But what if that assumption were wrong? What if 2 g of silica were sufficient, or what if it required 80 g of silica? In sensitivity analysis, LCA researchers vary such assumptions to higher and lower values. If synthesis #3 remains the greenest option even when the assumption is varied, then identifying that synthesis as the greenest can be considered reliable.

5.3 Teaching & Learning Impact-based Metrics

This section provides learning outcomes, strategies, examples, and activities for incorporating impact-based metrics into your chemistry curriculum.

5.3.1 Student Learning Outcomes

A good starting point for adding impact-based metrics into your curriculum is to evaluate your course learning outcomes (LOs). In particular, consider what you are asking students to do with the content they learn or values they calculate. Learning outcomes related to using formulas and calculating mass or yield can be enriched by asking students to consider the impact of that mass or compare the impacts of two chemicals or reactions after calculating mass. Table 5.3 summarizes this approach to updating learning outcomes. The rest of this section describes approaches for 1st-year and upper-year courses in detail, followed by specific examples.

As you can see in Table 5.3, one benefit of this approach is that it also provides a practical way to address the need for meaningful and relevant contexts in chemistry education¹⁰ (see Chapter 4), and demonstrates chemistry's role in working towards the UN Sustainable Development Goals (see Chapter 7).^{11,12}

Table 5.3 Summary of approaches to updating learning outcomes (LOs) to include impact.

Level	Traditional LO ("Students can...")	Updated LO to include impact
1st year Stoichiometry, ideal gas law	Balance a reaction equation and calculate the mass of an ideal gas from moles.	Determine which of two gasses is more harmful by balancing reaction equations and calculating the ideal gas mass from moles.
1st year Yield, limiting reagents	Derive the theoretical yield and calculate percent yield for a reaction under specified conditions.	Determine the environmental harm caused by a reaction based on its theoretical and percent yield under two specified conditions.
1st year Structure and properties	Describe the role of intermolecular forces on the viscosity of liquids.	Describe the role of intermolecular forces on the viscosity of liquids and the trade-off of desired properties with potential for harm.
Upper-year Organic	Use retrosynthetic analysis to design plausible syntheses from readily available materials.	Use retrosynthetic analysis to design plausible syntheses from readily available and environmentally benign materials.
Upper-year Inorganic	Predict the reactivity of transition metal complexes based on the type of metal, its oxidation state, and ligands.	Predict the reactivity and potential for abiotic depletion of transition metal complexes based on the type of metal, oxidation state, and ligands.

5.3.2 First-year Chemistry and the First-year Undergraduate Curricula

As first-year chemistry is required for students majoring in chemistry, chemical engineering, and related disciplines, it is the ideal place to introduce the concepts of green chemistry. With respect to metrics, we believe the key learning outcome is that students are able to:

distinguish the greenest of two or more options and explain their reasoning in terms of the potential for environmental harm.

By the end of first-year chemistry, students should be able to answer questions such as: Which chemical, A or B, would cause less environmental harm? Which process, X or Y, would result in less environmental harm?

Many questions in the first-year undergraduate chemistry curriculum ask students to calculate the mass of a chemical. Any such question can be modified to have the students do the same calculation for two chemicals and subsequently compare these two in terms of harm.⁹ Students can practice these decision-making skills within the existing content of the first-year curriculum, for example, when learning how to use the ideal gas law to calculate the mass of a gas. Practice questions can be designed to have students use the ideal gas law but also use the result to select the less harmful of two options. This approach, shown in Box 5.5, illustrates how impact is integrated into the question while keeping the intended learning outcome (gas laws) and its calculation steps intact. To use this approach, it is only necessary for instructors to briefly introduce the concept of green chemistry and the equation that determines impact (Box 5.3 or Box 5.4).

5.3.3 Introductory Organic Chemistry: organicallychem.com

For educators looking to teach organic chemistry using green and sustainable chemistry principles, organicallychem.com is a freely available set of “plug and play” modules (SCORM12, PDF, pptx).¹³ These modules cover essential organic chemistry topics, allowing students to explore how organic chemistry relates to impact-based metrics, sustainability, and renewable resources. The modules are designed for students with varying levels of chemistry experience. Each module is a stand-alone introductory lesson that can be used to enhance or replace existing organic chemistry teaching materials. We recommend pairing all modules with “Module 0: Introduction to Organic Chemistry,” which introduces impact-based metrics and the philosophy of green chemistry and is an approachable introduction to organic chemistry concepts for high school, first-year or second-year students. The entire set also can be used as an introduction to an organic chemistry course and includes an additional question bank.

Module 1: Structure and Properties asks learners to consider the environmental and human impacts of chemicals and gets them thinking about

Box 5.5 An example 1st year undergraduate question that has students practice calculating impact and choosing the less harmful option within the context of a type of calculation that is already an expected part of the curriculum.

QUESTION: HCFCs (hydrochlorofluorocarbons) are sometimes used as refrigerant gases. Before it is turned on, an air conditioner with an internal volume of 70 L holds 8.0 atm of refrigerant at 20 °C. The operator of the air conditioner is considering using either CHF₂Cl or CH₃CFCl₂ as the refrigerant gas. For each gas, calculate the mass required. Which gas would cause the least ozone depletion if it escaped?

Chemical	MW (g mol ⁻¹)	P _{OD} (ozone depletion potential)
CHF ₂ Cl	86.47	0.055
CH ₃ CFCl ₂	116.94	0.11

ANSWER: $PV = nRT = (m/M)RT$

$$m_{\text{CHF}_2\text{Cl}} = MPV/RT$$

$$= 86.5 \text{ g mol}^{-1} \times 8.0 \text{ atm} \times 70 \text{ L} / (0.0821 \text{ L atm K}^{-1} \text{ mol}^{-1} \times 293 \text{ K})$$

$$= 2013 \text{ g}$$

Ozone depletion from CHF₂Cl = 2013 g × 0.055 = 110 g

$$m_{\text{CH}_3\text{CFCl}_2} = MPV/RT$$

$$= 116.94 \text{ g mol}^{-1} \times 8.0 \text{ atm} \times 70 \text{ L} / (0.0821 \text{ L atm K}^{-1} \text{ mol}^{-1} \times 293 \text{ K})$$

$$= 2722 \text{ g}$$

Ozone depletion from CH₃CFCl₂ = 2722 g × 0.11 = 300 g

Therefore CHF₂Cl would cause the least ozone depletion.

toxicity and molecular design. The module provides a comprehensive overview of how structure relates to function. It covers intermolecular forces and functional groups and how these relate to polarity, solubility, and toxicity. While impact-based metrics from this chapter are not used explicitly, the module focuses on being able to predict toxicity using a simple metric related to impact: the octanol-water partition coefficient (log *K*_{OW}). The module is suitable for any introductory organic chemistry course, *e.g.*, at the first- or second-year level.

Module 2: Stereochemistry and *Module 3: Nucleophilic Substitution and Addition* build on this concept that structure can dictate function and toxicity. For example, Module 3 explores ideas of electrophilicity and how this reactivity can create “excess toxicity” when considering mechanisms for reactions with enzymes. This module is suitable for students who have completed an introductory organic chemistry course that covers the basics of substitution reactions.

5.3.4 Upper-level or Specialized Undergraduate Curriculum

In upper-level chemistry courses, selecting the greenest chemical will not be sufficient—students need to be able to identify the greenest synthesis. Here the key learning outcome is:

Given two or more syntheses of a product from a given starting material and reagents, identify which synthesis causes the least harm.

Fortunately, simple calculations can still answer more complex questions by using the equation $I = P \times m$ (example shown in Box 5.6) or by having the students do a Life Cycle Assessment. The latter is preferable if time permits.

However, the approach in Box 5.6 only considers one environmental impact, which in real life could lead to *risk migration*, which was defined earlier as an option better in one impact but problematic in another. In an earlier example, the second route produces less harm from global warming but may have the highest ecotoxicity impact. To understand the full picture, Life Cycle Assessment can be taught in an upper-year course, with the lectures accompanied by a major assignment so that the students can practice their skills.¹⁴ Students who did this exercise at Queen's University and at the ACS Summer School on Green Chemistry reported afterwards that they found it gave them a much clearer picture of what features in a synthesis are typically the most harmful.

5.3.5 Activities and Practical Examples for Impact-based Metrics

5.3.5.1 Peer Teaching (Jigsaw) Introductory Activity

Since LCA is complex and involves many different metrics, it can be helpful to scaffold students' learning using a 'jigsaw' or peer teaching activity.¹⁵ This approach introduces single metrics, followed by peer teaching to consider all metrics when making a decision about which synthetic route is greenest. The learning outcomes (LOs) are:

1. Describe various impact-based metrics and their relationship to green chemistry principles, including safety, waste production, and the environment.
2. Use data to calculate the potential and impact of a reaction or process.
3. Use impact-based metrics to compare and contrast different processes and decide which process is greenest based on those metrics.
4. Rationalize how different contexts might influence which process is greenest when considering different impact-based metrics.

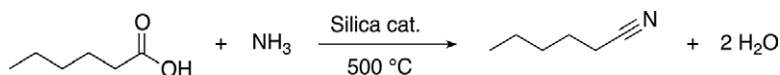
The four-step activity described next was designed so that students had a choice between three different synthetic routes to produce 1-fluorohexane

Box 5.6 Example question that has students compare two syntheses in terms of one environmental impact.

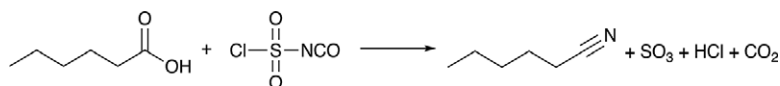
QUESTION: Compare these two syntheses of 1 mole of hexanenitrile. Considering only the gaseous waste (SO_3 , HCl , CO_2 , unreacted NH_3), which route would cause the least acid rain?

HCl MW = 36.5 g mol^{-1} , Acidification Potential = 0.88
 NH_3 MW = 17.0 g mol^{-1} , Acidification Potential = 1.88
 CO_2 MW = 44.0 g mol^{-1} , Acidification Potential = 0
 SO_3 MW = 80.1 g mol^{-1} , Acidification Potential = 0.80

Route 1: Hexanoic acid (116 g, 1 mol) and ammonia (10 mol) were reacted over 480 g of silica at 500°C . The product was captured in a condenser but the unreacted ammonia was allowed to escape (simplified from *J. Am. Chem. Soc.* **1931**, 53 (1), 321).



Route 2: Hexanoic acid (116 g, 1 mol) was added to a solution of chlorosulfonyl isocyanate (141 g) in benzene (250 mL) and stirred for 30 min at 60°C . Volatiles were removed from the product mixture by distillation, giving the product hexanenitrile (simplified from *Chem. Ber.*, **1967**, 100, 2719).



ANSWER

Route 1: moles of unreacted $\text{NH}_3 = 10 - 1 \text{ mol} = 9 \text{ mol}$
 mass of unreacted $\text{NH}_3 = 9 \text{ mol} \times 17.0 \text{ g mol}^{-1} = 153 \text{ g}$
 acid rain impact = $153 \text{ g} \times 0.80 = 122 \text{ g}$

Route 2: moles of each acid gas = 1 mol (each)
 mass of $\text{SO}_3 = 1 \text{ mol} \times 80.1 \text{ g mol}^{-1} = 80.1 \text{ g}$
 mass of $\text{HCl} = 1 \text{ mol} \times 36.5 \text{ g mol}^{-1} = 36.5 \text{ g}$
 mass of $\text{CO}_2 = 1 \text{ mol} \times 44.0 \text{ g mol}^{-1} = 44.0 \text{ g}$
 acid rain impact = $(80.1 \text{ g} \times 0.80) + (36.5 \text{ g} \times 0.88) + (44.0 \text{ g} \times 0) = 96 \text{ g}$
 Therefore, the second route would cause the least acid rain.

(1-hexylfluoride). Of the three routes, two were selected to have relatively similar impact indices when compared using LCA, and the other was obviously the worst overall, so students would need to engage in multivariate reasoning and systems thinking to reach an answer. Students were given the added context that “the chemical plant is located on the banks of a river used by humans for swimming and fishing” to encourage

students to consider different contexts and necessary trade-offs in their decision.

1. **Introduction, ~ 5 minutes.** In class, students are given an outline of the activity and its intended learning outcomes. Before the class, students should review the basics of each impact-based metric. The set-up of the jigsaw activity depends on how many metrics you want to include; for this example, we will use five metrics: abiotic depletion, smog formation, global warming, human ingestion toxicity, and human inhalation toxicity. This includes how it is calculated, from what reference compound, and where to find potentials used in calculations.
2. **Single metric, ~15 minutes.** Split the class into five equal-sized groups (or one for each metric you use). Each group is assigned an impact-based metric and introduced to its basics by a facilitator or with a print-out. All groups are given the same situation, which involves choosing the greenest route for a chemical product out of several alternatives. For each student, have a printed worksheet with information about the chemical processes and empty tables to fill. One version for each impact-based metric potential is needed. Working within their group, individuals will calculate the indices of their metric for each route based on the provided impact potentials.
3. **Peer teaching, ~10 minutes.** New teams are now formed with one member from each of the earlier groups. In this way, each team has one “expert” (for the scope of this activity) in each impact-based metric. In these teams, students work together using what they learned in the first stage to determine which process is greenest, but now considering all five metrics. First, the teams compile their data in a single LCA table. Next, students should deliberate as a team to identify which they believe is the greenest route. Students should be encouraged to consider each route’s pros and cons (*i.e.*, trade-offs and risk migration). Finally, each team must decide on one route and present their final verdict.
4. **Share, ~15 minutes.** Each team nominates one representative to share their choice, justification, and reasoning with the class.

This activity was published open-access with full details and worksheets available as supporting information.⁹ Short surveys run before and after the activity showed that students felt more confident in their abilities on each learning outcome (listed earlier) and enjoyed the classroom activity.

5.3.5.2 Teaching Molecular Design for Decreased Environmental Impact

The preceding discussion is predicated upon the assumption that the instructor gives the students options (for example, Box 5.5). In upper-year

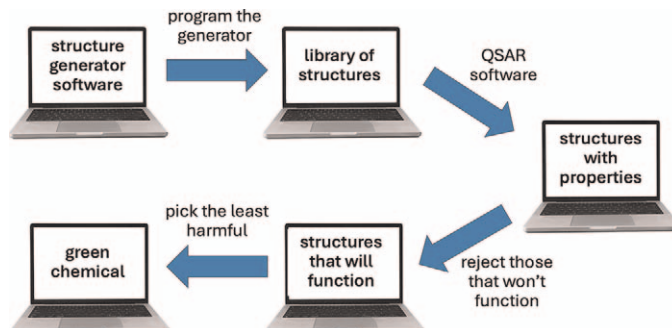


Figure 5.2 The process by which students can use virtual screening to identify candidate molecules for a task and then choose the least harmful among them. This figure contains original artwork.

courses, students will be more empowered as future practicing green chemists if they can learn to identify options on their own. Thus, the next pedagogical outcome could be to teach *molecular design*. Specifically, *how would a chemist identify candidate molecules that would meet the required properties for an application and be as green as possible?* This skill can be taught using computer-aided virtual screening.

Specifically, students would be tasked with using freely available structure-generator software to create a molecular structure library and then to use QSAR (quantitative structure–activity relationship) software to predict the properties of the chemicals in the library (Figure 5.2). Those molecules with the required properties can be identified from that data, and the least harmful among them can be selected. An example assignment is shown in Box 5.7. A web-based structure generator that works on both Mac and Windows platforms is available at ChemInfo.org. The EPA website offers a QSAR program called TEST (Toxicity Estimation Software Tool), which was available on both platforms in the past but, unfortunately, the EPA no longer updates the Mac version. Detailed instructions on this assignment have been published.¹⁶

5.3.5.3 Advanced Exercise: Life Cycle Assessment

Conducting a Life Cycle Assessment for any product is laborious, as it requires searching for and compiling data, setting system boundaries, and making difficult decisions from dozens of variables. Unsurprisingly, teaching Life Cycle Assessment within the constraints of class periods, 3–6 month school terms, and an already crowded curriculum is a huge challenge. If at all, this topic is typically covered only in upper-year post-secondary chemistry or environmental science elective courses, which can take 4–6 weeks to complete.

However, the standard and detail needed for introducing LCA to chemistry students need not be as high as would be required to teach future LCA

Box 5.7 An example assignment that has students practice virtual screening in the programs ChemT (sites.esa.ipb.pt/medchem/chemt) and TEST (epa.gov/comptox-tools/toxicity-estimation-software-tool-test), for the purposes of identifying candidate chemicals for a specified task and then choosing the least harmful among them.

QUESTION: Imagine that you are working for a company that makes detergents and textile chemicals using dialkyl sulfoxides, $RS(O)R'$, where the two R groups are uncharged and could be identical or different. You have been tasked with identifying a sulfoxide with a boiling point (T_b) above 200 °C and low toxicity to mammals and invertebrates, represented by rat LD_{50} and daphnia magna LC_{50} 48 h. You will do this by generating a library of at least 20 different sulfoxides in ChemT, predicting their T_b and toxicities using the TEST program, and then analyzing the results to choose the best option that meets your criteria.

1. Write all of your compounds in a table using the following headings.

Sulfoxide name	Predicted T_b (°C)	Predicted rat oral LD_{50} ($g\ kg^{-1}$)	Predicted daphnia LC_{50} ($g\ L^{-1}$)

2. Which sulfoxide would you recommend based upon the given criteria? Explain.

practitioners. Its steps include valuable learning outcomes such as defining system boundaries, case comparisons, systematic calculations, and critical thinking for multivariate decision-making. Here, we provide an LCA exercise used in an upper-year elective green chemistry course. Its learning outcomes are the same as the activity in Section 5.3.5.1, but less information and data are given to the students, and more routes are considered.

5.3.5.3.1 Format. The LCA exercise taught by one of the authors (PGJ) has the students work in teams of 4 to 7 members. Each team is given a transformation, such as converting benzene to aniline, and four or five literature preparations for achieving their assigned transformation. The team is expected to mathematically scale each synthesis to make 1 kg of product and to calculate the harm that would be caused by performing the synthesis at that scale. No experimental work is performed; this is a paper exercise. Details of this exercise have been published,¹⁴ although we now find it better to omit the ODP (Ozone Depletion Potential), PER (persistence), and ACCU (bioaccumulation)

metrics and use Photochemical Ozone Creation rather than Smog Formation. Guidance for instructors and students on finding and/or calculating potentials is also available in the supplementary material of a related article.⁹

This exercise is a gate-to-gate LCA, rather than cradle-to-grave, to prevent excessive time commitments from students and grading. Students are taught in lectures that gate-to-gate LCAs are not preferred because they fail to consider the environmental harm of making the starting materials and reagents. Nevertheless, the learning objectives are met, and the students often discuss this limitation when they report back to the class.

5.3.5.3.2 Content and Considerations. The instructor selects literature preparations to ensure a diverse range of techniques. For example, the set of preparations may include syntheses at high temperature *vs.* room temperature, catalytic *vs.* stoichiometric agents, with and without post-reaction chromatographic purification, with good *vs.* poor yields, *etc.*

In the preceding lectures, the students must learn the basics of LCA. In addition, either the lectures or the instructions accompanying the assignment must cover:

- how to numerically scale up the preparations to 1 kg;
- what assumptions to make when details are missing (*e.g.*, how much drying agent is used?);
- how to find or calculate the potentials;
- how to calculate energy consumption and the corresponding harm;
- how to estimate emission rates;
- how to consider the emissions of air-sensitive compounds:

e.g., emission of 1 mol of LiAlH_4
= emission of 1 mol of LiOH and 1 mol of $\text{Al}(\text{OH})_3$.

Emission rates must be estimated when they are not measured directly. These emission rates are suggested:

- 1% emission for the product and anything that can be recycled, reused, or sent for incineration after the synthesis;
- 100% emission for drying agents, column packing agents, non-combustible byproducts, non-recyclable catalysts, and the like;
- 100% of what is left after the reaction or 1% of the original amount (whichever is greater) for inorganic reagents that are partly or completely consumed in the reaction.

In addition to calculating the harm related to various chemicals and emissions, students must also calculate the harm caused by energy usage in the process (Box 5.8). Once teams have calculated the energy consumption

Box 5.8 Calculating energy consumption for heating liquids. For simplicity, these equations assume no heat losses. m is the mass, C_p is the heat capacity in $\text{J g}^{-1} \text{K}^{-1}$, T_f is the final temperature and T_b is the boiling point. ΔH_{vap} is the heat of vaporization in J g^{-1} . n is the number of times the average solvent molecule is refluxed during the time of refluxing. This depends greatly on the conditions but assume n is 1 for every half hour.

To heat a liquid: $q = m C_p (T_f - 20 \text{ }^\circ\text{C})$

To distill a liquid: $q = m C_p (T_b - 20 \text{ }^\circ\text{C}) + m \Delta H_{\text{vap}}$

To reflux a liquid: $q = m C_p (T_b - 20 \text{ }^\circ\text{C}) + n m \Delta H_{\text{vap}}$

required for heating reaction mixtures or distilling solvents, they can calculate the harm caused by generating that much energy (Table 5.4). For this calculation, teams should be assigned a country in which their hypothetical syntheses will take place.

5.3.5.3.3 LCA Exercise Assessment. After doing the calculations, students submit a report and present their results to the class. Their presentation includes a description of each synthesis and its major sources of harm, recommendations on how to reduce the harm of each synthesis, and an overall table comparing the studied syntheses (Table 5.2). In that table, the students are encouraged to color the worst option in each column in red, the best in green, and the others in yellow. This allows the audience to quickly assess the various options in terms of each impact. Students are also instructed to round values to only a single significant digit so as not to overstate the accuracy of the calculation. While showing this overall table to the class, the team members will identify which synthesis they recommend as the greenest and explain why. Students must mention the effect of the energy-associated harm on their decision-making process. The team report is graded on the accuracy of the calculations, explanation and reasonableness of assumptions, reasoning for the selection of the greenest synthesis, identification of the most problematic chemicals, and suggestions for improvements for each route. The presentation is graded on presentation skills, quality of the explanation, and ability to answer questions.

5.4 Closing Thoughts

Green chemistry education has relied for too long on qualitative generalizations and mass-based quantitative metrics. Qualitative generalizations will always have an important role to play in early green chemistry education, but this chapter emphasizes that mass-based metrics should be largely replaced by impact-based metrics. The primary goal of green chemistry is the

Table 5.4 The approximate impact of electricity production^a in various countries.

Country	Acidification	Smog formation	Global warming	Freshwater eutrophication	Human toxicity	Resource depletion
Australia	1.3	2.2	620	6.0×10^{-4}	33	3.0×10^{-3}
Brazil	0.20	0.72	80	13.2×10^{-4}	19	1.6×10^{-3}
Canada	0.20	0.73	140	5.7×10^{-4}	6	1.0×10^{-3}
China	1.6	2.6	700	6.7×10^{-4}	36	1.4×10^{-3}
S Africa	2.1	3.4	920	4.7×10^{-4}	44	1.4×10^{-3}
UK	0.36	0.97	240	18.1×10^{-4}	26	1.7×10^{-3}
USA	0.58	1.3	400	5.7×10^{-4}	13	1.8×10^{-3}
Units ^b	g SO ₂ eq	g C ₂ H ₄ eq	g CO ₂ eq	g PO ₄ eq	g DCB eq	g Sb eq

^a Per 1 kW h or 3600 kJ. Calculated from the reported electricity mix for each country in 2023 and the typical harm caused by each of the primary energy sources (see reference Barros *et al.*).

^b Units are all in the format grams of [reference chemical] equivalents. DCB: 1,4-dichlorobenzene.

avoidance of harm, and this is best conveyed by teaching students how to quantify harm and how to make quantitative comparisons in terms of harm.

The tools described in this chapter illustrate how impact-based metrics can be added to the undergraduate curriculum in a variety of ways and at several levels. The simplest is using a single impact-based metric to compare two chemicals, which is suitable for first-year undergraduate chemistry courses. Because such questions are easily tagged onto calculation questions already used in the curriculum, the coverage of these metrics takes very little time in the course and, therefore, need not displace existing content. The most complex example discussed in this chapter is a gate-to-gate LCA assignment that, while not meeting the exacting standards of a publishable LCA, gives the students an idea of how LCA is done, how the results are interpreted, and the kinds of features that make a synthesis more harmful.

During the discussion of impact metrics, especially in the discussion of LCA, it is important to convey to the students that some impacts cannot (yet) be quantified. Biodiversity loss, social impacts, and persistent plastic pollution are examples of impacts that are not yet adequately quantifiable. In real-world decision-making, such impacts need to be considered along with those that are easier to quantify.

References

1. C. Edwards and J. M. Fry, *Life cycle assessment of supermarket carrier bags: a review of the bags available in 2006*, Environment Agency, Bristol, UK, 2011.
2. A. Ahamed, P. Vallam, N. S. Iyer, A. Veksha, J. Bobacka and G. Lisak, *J. Cleaner Prod.*, 2021, **278**, 123956.
3. Life Cycle Assessment of grocery carrier bags, Danish Environmental Protection Agency, København Ø, 2018.
4. B. Trost, *Science*, 1991, **254**, 1471.
5. R. A. Sheldon, *Chem. Ind.*, 1992, 903.
6. R. A. Sheldon, *Green Chem.*, 2017, **19**, 18.
7. T. A. Holme and J. E. Hutchison, *J. Chem. Educ.*, 2018, **95**, 499.
8. *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards*, ed. H. De Bruijn, R. Van Duin, M. A. J. Huijbregts, J. B. Guinee, M. Gorree, R. Heijungs, G. Huppes, R. Kleijn, A. De Koning, L. Van Oers, A. Wegener Sleeswijk, S. Suh and H. A. Udo De Haes, Springer Netherlands, Dordrecht, 2002, vol. 7.
9. J. De Verteuil, P. G. Jessop and A. Bongers, *J. Chem. Educ.*, 2024, **101**, 1592.
10. P. G. Mahaffy, T. A. Holme, L. Martin-Visscher, B. E. Martin, A. Versprille, M. Kirchhoff, L. McKenzie and M. Towns, *J. Chem. Educ.*, 2017, **94**, 1027.
11. P. G. Mahaffy, S. A. Matlin, J. M. Whalen and T. A. Holme, *J. Chem. Educ.*, 2019, **96**, 2730.

12. United Nations Sustainable Development Goals, <https://sdgs.un.org/goals> (accessed August 2025).
13. Organically Chem, <https://organicallychem.com/> (accessed August 2025).
14. S. M. Mercer, J. Andraos and P. G. Jessop, *J. Chem. Educ.*, 2012, **89**, 215.
15. E. Aronson, N. Blaney, C. Stephin, J. Sikes and M. Snapp, *The Jigsaw Classroom*, Sage Publishing Company, Beverly Hills, CA, 1978.
16. J. R. Vanderveen and P. G. Jessop, *J. Chem. Educ.*, 2021, **98**, 2341.

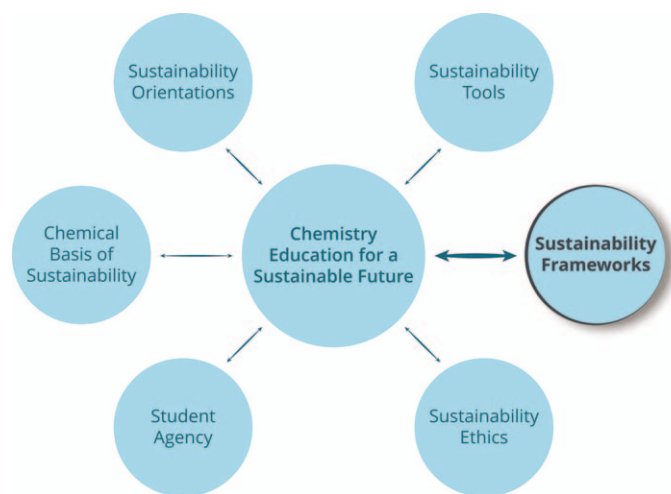
CHAPTER 6

Sustainability Frameworks I – Planetary Boundaries[†]

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6.1 Opening Thoughts: Tracking Global Environmental Unsustainability Using the Planetary Boundaries Framework

6.1.1 Unsustainability is a Global Systems Challenge

The rapidly increasing environmental unsustainability that people and the planet experience in the 21st century is a direct outcome of human activities to harness energy and transform matter. Especially since the Industrial Revolution of the mid-18th century, technological, cultural and socio-economic changes, fueled largely by the combustion of fossil fuels, have provided the energy and material transformation wants and needs of Earth's rapidly growing population. The rate of material transformation increased most notably in the period of "great acceleration" that began in the 1950s. One striking example that demonstrates the scale of human-caused planetary change is the determination, using standard methods of material flow analysis, that in 2020, both the mass of materials created by humans (anthropogenic "stuff")¹ and the total mass of carbon dioxide produced by human activity have now surpassed the dry mass of all living biomass.^{2,3}

Tackling environmental unsustainability starts with a scientific understanding of Earth as a complex system characterized by multiple components. Earth behaves as a tightly coupled biophysical system, in which life on Earth adapts and coevolves in response to changes in these components. The conditions that emerge from the interactions of these components determine whether people and the planet flourish.

One key component is the balanced flow of energy between incoming solar energy, mostly in the form of visible light, and outgoing energy emitted by Earth, mostly in the form of heat or infrared energy. Human activities that alter the chemistry of the atmosphere, for example by emitting greenhouse gases or sulfate aerosols, are changing this radiative balance.

Materials and their transformation, both through natural processes and through human activity, form a second key component. For many chemical elements, today's patterns of consumption will eventually limit their availability as elements become more dispersed and become more difficult to access and use.⁴ Everything in Earth's system can be categorized into smaller subsystems with their own distinct behavior. These include the atmosphere (air), biosphere (living things), lithosphere (Earth's crust), hydrosphere (water), and the cryosphere, a subcategory of the hydrosphere that consists of the frozen parts of Earth.

6.1.2 The Planetary Boundaries Framework Shows How People are Changing the Planet

The Planetary Boundaries framework⁵ shows the importance of considering the Earth as a system to analyze, quantify, and where possible, predict environmental changes and their impacts on people and the planet.

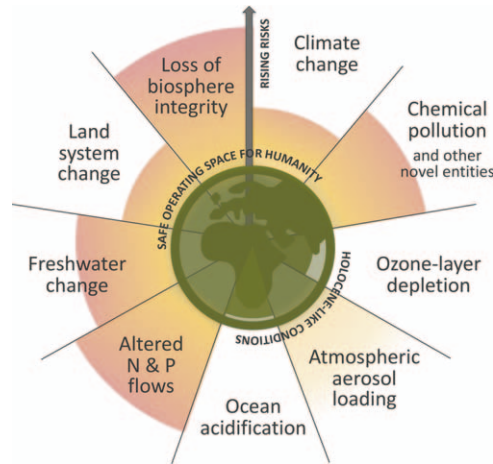


Figure 6.1 A visualization of the Planetary Boundaries framework. Human-caused pressures on nine Earth system processes are driving the world away from stable environmental conditions (the green Holocene world) to a situation of rising uncertainty about future conditions and complex systemic risks. The amber-red wedges represent the current situation, assessed in terms of “control variables” for each Earth system process that tracks long-term, large-scale change. Note that the control variable for atmospheric aerosol loading is quantified as the difference between north and south hemispheres, rather than a globally assessed quantity, which is why it is shaded differently. Image by S. Cornell. Data from ref. 13, with assessments in ref. 7, 14 and 15.

The Planetary Boundaries framework (Figure 6.1) was devised in 2009 by an international group of global environmental change scientists with expertise in the behavior of Earth’s various subsystems. It highlights a suite of physical, ecological, and biogeochemical changes that are happening at a planetary scale. Multiple updates to the framework have been published since then,^{6–8} improving its usefulness in Earth system research and in sustainability initiatives. Businesses use the framework for setting targets to minimize their environmental impacts,^{9,10} and policymakers use it to develop strategies that deal better with systemic links between social, economic, and environmental problems,¹¹ especially in Europe where there is a long-term objective to “live well, within planetary boundaries”.¹²

The Planetary Boundaries framework consists of nine Earth system processes in which present-day human activities are disturbing Earth’s material flows and energy balance (Figure 6.1). Each Earth system process in the framework is represented in terms of at least one globally quantifiable metric or control variable, using data from Earth system models and Earth observation systems. Individually, the environmental changes included in the framework are often reasons for local concern, but the framework highlights that when these changes happen in combination, they have very large-scale and long-term consequences for the Earth system as a whole.

Earth's environment has varied greatly over geological time, but human societies only established themselves worldwide during the Holocene Epoch, when climate and ecological conditions were relatively stable. In the most widely used diagrams of the framework, this baseline of stable biophysical conditions is shown as a green "safe operating space for humanity". Earth's history gives evidence that when the planetary boundaries are overstepped, rapid and irreversible changes can play out over large parts of the world. As Earth's biophysical conditions become less stable and less predictable, living ecosystems – including the world's societies – will find it harder to adapt to change. This means that the Planetary Boundaries framework is also useful for highlighting the rising risks of today's linked environmental changes.

The extent of human-caused changes away from the stable baseline is shown as an intensifying amber to red wedge. Estimates of the natural variability and other sources of scientific uncertainty are taken into account. Taking climate change as an example, the atmospheric carbon dioxide concentration during the 12 000 years of the Holocene Epoch that followed the last Glacial Period was around 280 ppm. Although this value fluctuated for natural reasons, the concentration stayed well below 350 ppm, the value at which the climate change planetary boundary has been positioned. Today, the concentration of carbon dioxide in the atmosphere exceeds 425 ppm, well outside the range for a stable climate (over the coming decades at least), and contributes directly to global warming and changes to other essential climate variables that already have harmful and expensive impacts.

In the Planetary Boundaries framework, climate change and biosphere integrity (most simply understood as loss of biodiversity) are considered core boundaries because together, these two planetary processes define the biophysical state of the Earth system and characterize Earth's shifts between geological epochs. Feedback between the physical climate and the living biosphere plays a controlling role in Earth's stability and change. Breaching either one of these planetary boundaries drives the Earth system into a new state, with irreversible consequences should they be substantially and persistently transgressed. Overstepping the climate change planetary boundary irreversibly changes the conditions for all living organisms; changing large-scale ecosystems through processes like deforestation and intensive agriculture fundamentally alters the flows of heat and water that make up the climate. Land system change and freshwater change capture the main direct drivers of change in the core boundaries through people's use of natural resources. The other processes in the framework tackle the most important disruptors to biophysical and biogeochemical feedbacks in the Earth system, including through the synthesis and mobilization of pollutants.

6.2 Background: Education for Global Environmental Sustainability

At both secondary and post-secondary levels, current approaches to teaching chemistry often emphasize the mastery of fragmented topics to equip

students with disciplinary depth. While this outcome has considerable value, opportunities are often missed to empower students to relate fundamental understanding in chemistry to the complex sustainability challenges facing Earth and societal systems. However, recent initiatives are gaining considerable traction for reimagining chemistry teaching and learning through systems thinking¹⁷ so as to better build transferable knowledge and skills that can be applied to global challenges.¹⁸

The IUPAC Systems Thinking in Chemistry Education (STICE) project¹⁹ tackled this educational challenge with project outcomes including a special issue of the *Journal of Chemical Education* devoted to systems thinking and green & sustainable chemistry education.²⁰ It was followed up with the IUPAC project²¹ on Systems Thinking in Chemistry for Sustainability: Toward 2030 and Beyond (STCS 2030+), which describes systems thinking as the ability to understand and interpret complex problems, viewing a system as a whole and not just a collection of parts.²² Chapter 4 provides further detail about how systems thinking approaches can promote meaningful learning of chemistry content, while equipping students to use their knowledge of chemistry to understand and address global sustainability challenges.

Beyond mastery of isolated central ideas in chemistry, chemistry curricula should be designed to prepare critical and independent learners. Transformed curricula should be more question-driven than knowledge-driven and more authentic problem-based than topic-based. Sustainability challenges are at the top of the list of authentic problems faced by Earth and societal systems. Transformed chemistry education would introduce chemistry content in the context of Earth and societal systems and equip learners to address complexity.⁹

But transforming chemistry curricula is easier said than done. Chemistry educators who have themselves been taught with an emphasis on mastery of isolated concepts and disciplinary depth do not find it easy to pivot from traditional ways of educating in chemistry to the implementation of new learning outcomes (LOs) focused on the emergence of global environmental sustainability. How can educators get started in equipping chemistry students with the knowledge, skills, and orientations to better address the environmental unsustainability of global Earth systems?

A good starting point is to review LOs for existing chemistry courses and assess whether they integrate the mastery of chemistry concepts, theories, and laboratory experiences with sustainability goals.²³ Educators are then encouraged to articulate expanded LOs that equip students with a set of competencies that weave together three key dimensions: systems thinking (addressed through cross-cutting concepts), core understandings, and fundamental practices.²³ These three dimensions are consistent with those identified in the US Next Generation Science Standards (NGSS) for K-12 levels,²⁴ and have been expanded and adapted to guide the design, implementation, and evaluation of chemistry curricula, teaching practices, and assessments.²³

As visualized in Figure 6.2, the *central ideas* of chemistry (which are usually well represented in most listings of course learning outcomes) should be



Figure 6.2 Visualizing an approach to help chemistry educators get started in connecting traditional chemistry content to the emergence of sustainability by developing new learning outcomes focused on integrating the dimensions of systems thinking, core understandings, and fundamental practices. Reproduced from ref. 23 with permission from American Chemical Society, Copyright 2020. To whom requests for further permissions should be directed.

paired with two other sets of competencies that are often not articulated: *socio-environmental literacy*, which is the ability to understand, analyze, and communicate information about chemistry in the context of interconnected Earth and societal systems; and *socio-environmental responsibility*, which entails knowledge about the benefits, costs, and risks of interventions in these systems, and how they can be evaluated and managed by the good conduct of chemistry and chemists. Educating for global environmental sustainability also requires attention to fundamental practices and includes the *disciplinary practices* specific to chemical analysis, synthesis, and transformation; *science practices* that support investigation of authentic problems, including the critique and integration of data and information from other disciplines; and *collaborative problem-solving practices* that strengthen abilities to learn with and from each other, especially in the complex contexts of real-world practice.

The Planetary Boundaries framework provides a good example of how to use systems thinking as the underpinning form of reasoning to bring together core understandings and fundamental practices in chemistry education. A focus on human-caused Earth system changes provided by the Planetary Boundaries framework relates many central chemistry ideas with socio-environmental literacy and responsibility. This strategy prioritizes consideration of the nature of scientific evidence and engages students with collaborative problem-solving strategies using the tools of chemistry and science. This approach is illustrated in Section 6.3.1, which maps eight core chemistry topics onto Earth system processes in the Planetary Boundaries framework. Section 6.3.2 presents three sets of classroom-ready activities that demonstrate how to connect socio-environmental literacy and responsibility related to climate change to central chemistry ideas and fundamental scientific practices.

6.2.1 Structuring Chemistry Education for Sustainability Using the Planetary Boundaries Framework

Why describe the Planetary Boundaries framework and Earth's history in a book about chemistry education for a sustainable future? First, the framework brings together the main environmental impacts of the social and industrial uses of chemistry. People teaching and learning about chemistry should be informed about these consequences, and the Planetary Boundaries framework is one useful way to structure that learning process.

An open access interactive visualization and learning tool¹⁶ created by the King's Centre for Visualization in Science (KCVS) helps users understand sustainability challenges (Figure 6.3). This learning tool is a small computer program that runs in a web browser. The interactive tool shows the nine processes of the Planetary Boundaries framework, providing information about each process and explaining why they matter for Earth system behavior. It also dynamically shows the changes over time in each process since the Industrial Revolution and reveals the intensifying risks as shifts from green to amber to red play out simultaneously in the processes.

Second, the Planetary Boundaries framework also highlights the importance of systems thinking. Although its processes are usually treated as separate environmental problems, they are tightly linked through both biophysical and human-caused connections. A different part of the interactive learning tool shows the dynamic connections between the processes (Figure 6.4). At each connection point on this tool, the user can access information about the links among the Earth processes. By selecting the main nodes (the nine Earth system processes of the framework), all information relating to that process is provided at the same time. Figure 6.5 shows the

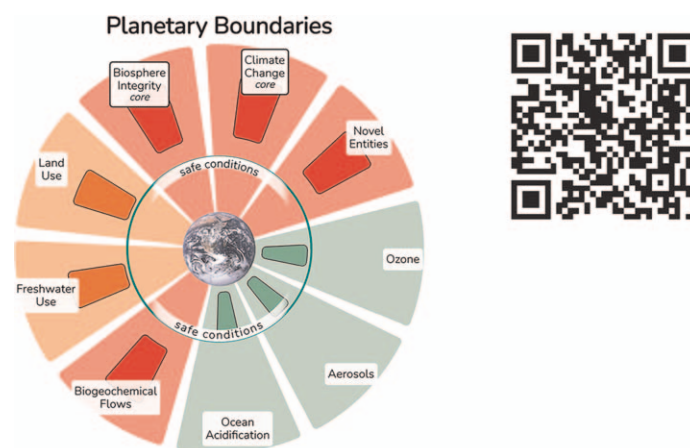


Figure 6.3 The interactive Planetary Boundaries learning tool (<https://applets.kcvs.ca/PlanetaryBoundaries/>),¹⁶ developed at the King's Centre for Visualization in Science. Image by P. Mahaffy.

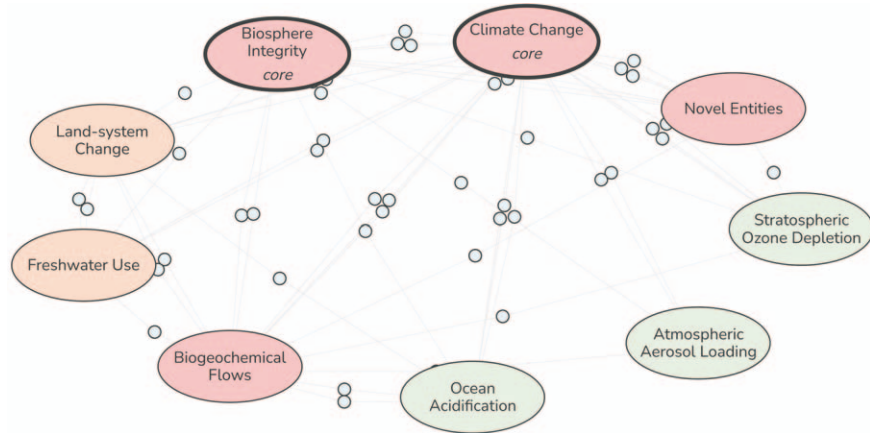


Figure 6.4 The web of connections among Planetary Boundaries: screenshot of the system connections tab of the interactive KCVS planetary boundaries learning tool,¹⁶ highlighting how the core boundaries (climate change and biosphere integrity) are linked to all other processes in the framework (<https://applets.kevs.ca/PlanetaryBoundaries/>, click on “connections” tab). Image by P. Mahaffy.

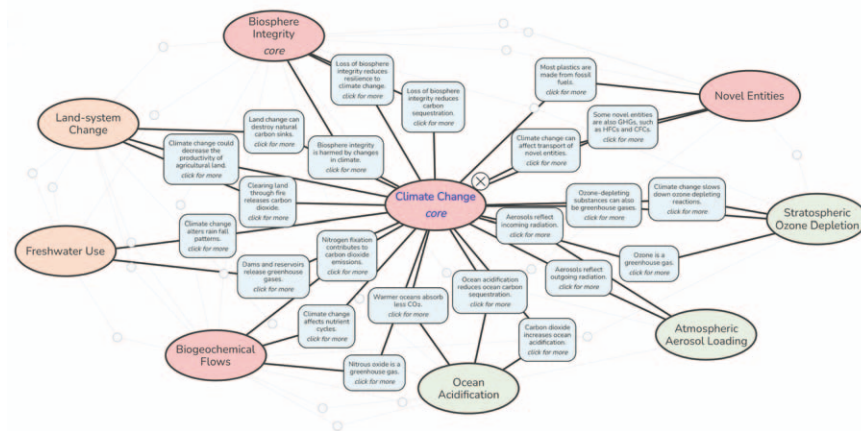


Figure 6.5 Screenshot of the system connections tab of the interactive KCVS planetary boundaries learning tool,¹⁶ visualizing the many links between climate change and the other eight processes (<https://applets.kevs.ca/PlanetaryBoundaries/>, click on “connections” tab). Image by P. Mahaffy.

information displayed when climate change is brought into focus in the interactive learning tool.

As the climate change example shows, chemistry plays a vital role in the Earth system connections that underlie the Planetary Boundaries framework. Many of the control variables that determine the state of Earth system

processes are chemical substances in air, water, or soil matrices. The Planetary Boundaries framework reveals just how much human activities are changing the chemical properties of the planet, in turn affecting Earth's physics and biology.

The Planetary Boundaries framework and this interactive learning tool provide an accessible entry for chemistry educators to orient their teaching toward a people-and-planet perspective, so as to emphasize environmental sustainability and better equip students for today's world of rapid and unpredictable changes.

6.3 Teaching and Learning Chemistry for Sustainable Earth and Societal Systems

6.3.1 Using the Planetary Boundaries Framework to Connect Chemistry and Sustainability

How can chemistry educators help their students relate core chemistry concepts to sustainability considerations? A visual representation of ways educators can relate core topics taught in foundational chemistry courses to Earth system processes in the Planetary Boundaries framework is shown in Figure 6.6, which is taken from the curriculum tab of the interactive KCVS Planetary Boundaries learning tool. In the interactive tool, clicking on each of eight core chemistry curriculum topics opens up suggestions for ways to relate that topic to an Earth system process.

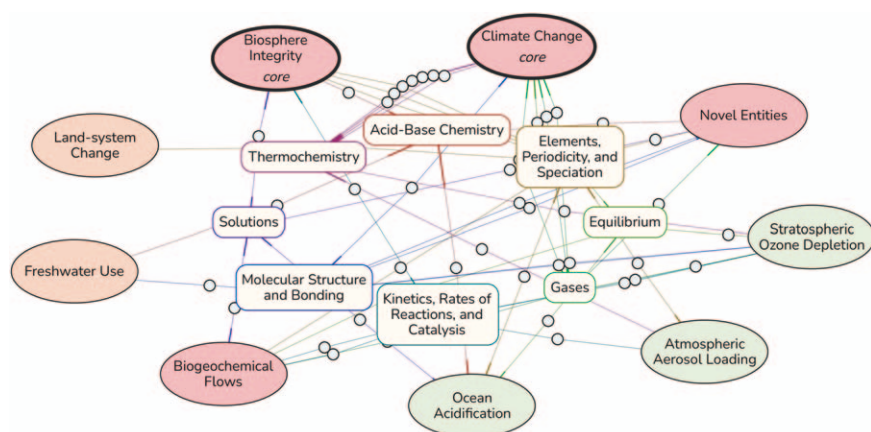


Figure 6.6 Screenshot of curriculum tab of the interactive KCVS Planetary Boundaries learning tool¹⁶ visualizing connections between eight core topics in chemistry and the Planetary Boundaries framework (<https://applets.kcvs.ca/PlanetaryBoundaries/>, click on “curriculum” tab). Image by P. Mahaffy.

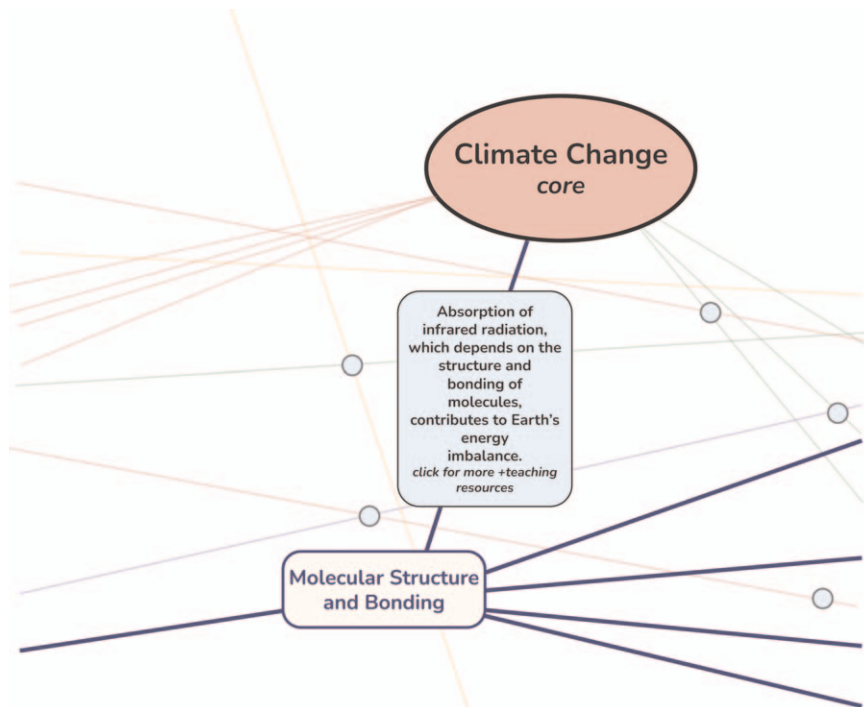


Figure 6.7 Chemistry curriculum topics are mapped onto Earth system processes in the interactive KCVS Planetary Boundaries learning tool.¹⁶ The screenshot from the curriculum tab of the learning tool shows learning resources available to map the topic of molecular structure and bonding onto the climate change Earth system process in the Planetary Boundaries framework (<https://applets.kcvs.ca/PlanetaryBoundaries/>, click on “curriculum” tab). Image by P. Mahaffy.

In the interactive learning tool, clicking on a core chemistry topic opens a textbox with a brief description of a central connecting idea. This is illustrated in Figure 6.7 in which the core chemistry topic “Molecular Structure and Bonding” is connected to the climate change Earth system process in the Planetary Boundaries framework. Clicking on that box opens a learning resources web page that describes the connection in more detail, listing key terms and presenting intended learning outcomes. This web page then links to a set of five interactive lessons and learning tools for students to work through to meet the learning outcomes.

Additional examples of how eight core chemistry topics that educators already teach can be mapped onto these Earth system processes can be found in Table 6.1. These examples were developed in collaboration with the task group for the IUPAC Project on Systems Thinking in Chemistry for Sustainability: Toward 2030 and Beyond.²¹

Table 6.1 Examples of ways to connect eight core chemistry topics to sustainability considerations by mapping them onto control variables for Earth system processes in the Planetary Boundaries framework.

Chemistry curriculum topic	Earth system process in the Planetary Boundaries framework	Example of connections and full descriptions of these and other connections can be found in the curriculum tab of the interactive KCVS planetary boundaries tool (Figure 6.3 and accompanying QR code)
Equilibrium	Ocean acidification	Simultaneous equilibria involving dissolved CO ₂ has impacts on ocean acidity, speciation of carbon, and biodiversity.
Equilibrium	Climate change	The oceans absorb approximately 30% of anthropogenic atmospheric CO ₂ through a series of simultaneous equilibria involving aqueous CO ₂ , carbonic acid, bicarbonate, and carbonate ions.
Acid–base chemistry	Biosphere integrity	Decreased water pH and less carbonate availability causes shells and skeletons of aquatic organisms to dissolve and become thinner or more brittle, placing the entire food web at risk.
Acid–base chemistry	Novel entities	Sulfur and nitrogen oxides from human activity react in the atmosphere to form acidic or acid-forming substances that deposit in aqueous and terrestrial environments and affect the health of fresh and saltwater ecosystems and soils.
Gases	Climate change	Chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), and other fluorinated gases, along with methane (CH ₄) and nitrous oxide (N ₂ O), are potent greenhouse gases that contribute to climate change.
Gases	Stratospheric ozone depletion	Chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), methyl bromide (CH ₃ Br), and nitrous oxide (N ₂ O) have molecular structures and physical properties that make them unreactive greenhouse gases in the troposphere. They can travel to the stratosphere where they are broken down by photochemical reactions and destroy stratospheric ozone in free radical catalytic cycles.
Solutions	Biogeochemical flows	Biogeochemical flows of nitrogen and phosphorus depend on the solubility of different species of those elements in water, which has a substantial impact on water quality and toxicity. Once P has been solubilized and used for fertilizer, it is difficult to recover.

Table 6.1 (Continued)

Chemistry curriculum topic	Earth system process in the Planetary Boundaries framework	Example of connections and full descriptions of these and other connections can be found in the curriculum tab of the interactive KCVS planetary boundaries tool (Figure 6.3 and accompanying QR code)
Solutions	Ocean acidification	Henry's law correlates the amount of dissolved CO ₂ in fresh and saltwater systems to the partial pressure of atmospheric CO ₂ . This is the first step in the simultaneous equilibria involving acid–base reactions that contribute to ocean acidification.
Elements, periodicity and speciation	Aerosols	Aerosols in the lower atmosphere can modify the size and color of cloud particles, directly affecting Earth's albedo and disrupting the cycling of water through Earth system processes and altering feedback loops that regulate climate.
Elements, periodicity and speciation	Biosphere integrity	An excess of available nitrogen and phosphorus species can cause eutrophication of soils and water, which can decrease the diversity of terrestrial and aquatic environments.
Molecular structure and bonding	Climate change	The absorption of infrared radiation by gases whose molecular structures make them greenhouse gases contributes to changes in radiative forcing, one of two control variables for the climate change Earth system process.
Molecular structure and bonding	Novel entities	Due to their large molecular masses and strong covalent bonds, single-use plastics are durable materials that accumulate on land and in oceans and break down to produce micro- and nano-plastics. These novel entities cause harm to terrestrial and aquatic life through inhalation, ingestion and strangulation.
Thermochemistry	Stratospheric ozone depletion	The net effect of the Chapman cycle of reactions that create and destroy ozone in the stratosphere is the conversion of UV light into heat at the top of the troposphere (the tropopause). This causes a reversal in the direction of the temperature profile moving from the troposphere to the stratosphere.
Thermochemistry	Climate change	Society relies on the transformation of energy stored in fossil fuels to power everything from our vehicles to our computers. However, our dependence on fossil fuels as a supply of energy alters Earth's energy balance that maintains our climate, as fossil fuel combustion produces greenhouse gases.

Table 6.1 (Continued)

Chemistry curriculum topic	Earth system process in the Planetary Boundaries framework	Example of connections and full descriptions of these and other connections can be found in the curriculum tab of the interactive KCVS planetary boundaries tool (Figure 6.3 and accompanying QR code)
Kinetics, rates of reactions, and catalysts	Biogeochemical flows	The Haber–Bosch process for nitrogen fixation at an industrial scale requires effective catalysts that reduce the temperature and lower energy requirements for the process, which currently consumes ~2% of the energy we produce on the planet.
Kinetics, rates of reactions, and catalysts	Stratospheric ozone depletion	The steady state concentration of ozone in the stratosphere results from the Chapman cycle of reactions involving O atoms, O ₂ molecules, and O ₃ . This equilibrium is perturbed by catalytic species such as chlorine and bromine atoms, and hydroxyl and nitric oxide radicals. A single free radical catalyst can destroy thousands of ozone molecules.

6.3.2 Teaching Chemistry and Climate Science with the Planetary Boundaries Framework

Practically, how might an educator teach chemistry in the context of the Planetary Boundaries framework while also helping students understand key aspects of sustainability science? We provide three activity sets focused on the climate change Earth system process that offer an entry point to equip students to deal with perhaps the most pressing sustainability challenge our planet faces. Since the Industrial Revolution and accelerating in the 1950s through the transition from the stable 12 000-year Holocene to the proposed Anthropocene Epoch, Earth’s energy balance has been rapidly altered by human activity that has increased atmospheric concentrations of both greenhouse gases and aerosols, driving rapid changes to Earth’s climate.

The climate change Earth system process has been designated one of two “core” processes (along with biosphere integrity), based on their fundamental importance to the stability of the entire Earth system, and because each has the potential on its own to drive the Earth system into a new state should they continue to be transgressed.⁷ Each of the two alternative control variables for climate change in the Planetary Boundaries framework is relevant for chemistry educators – the concentration of carbon dioxide in the atmosphere, and the change since the Industrial Revolution in Earth’s

Table 6.2 Two alternative control variables for the climate change Earth system process in the Planetary Boundaries framework, and their planetary boundary and current values. Both of these control variables substantially exceed their planetary boundaries and have passed into regions of “definitely high risk”.

Climate change Earth system process in the Planetary Boundaries framework		
Control variable	Planetary boundary value of the control variable	Present value of the control variable
Mean atmospheric CO ₂ concentration (ppm)	350 ppm CO ₂	424 ppm CO ₂ (November 2024 avg) ²⁵
Radiative forcing at top of the atmosphere relative to 1750 (W m ⁻²)	+1.0 W m ⁻²	3.1 W m ⁻² (2023) ²⁶

radiative forcing, the main driver for climate change. Both control variables have exceeded their planetary boundaries and are in regions of very high risk (Figure 6.1 and Table 6.2).

6.3.3 Activities and Resources to Connect Chemistry Concepts to Climate Change Through the Planetary Boundaries Framework

This section presents three activity sets for students and their instructors using open access interactive KCVS learning tools. All three connect foundational chemistry concepts to the climate change Earth system process in the Planetary Boundaries framework. The first activity set introduces the concept of Earth’s energy balance and the term radiative forcing. The second progresses to examine the chemical substances that have caused the greatest positive and negative radiative forcing since the Industrial Revolution, and the third activity set explores what makes a chemical substance a significant greenhouse gas and positive radiative forcer. Each activity set is introduced with a set of learning outcomes and identifies the key chemistry and sustainability concepts as well as connections to the Planetary Boundaries framework.

6.3.3.1 What Factors Control Earth’s Energy Balance?

Earth’s energy imbalance is the difference between the energy coming in from the sun, mostly in the visible and infrared regions of the electromagnetic spectrum, and the energy reflected back into space as visible light and emitted by the Earth in the form of infrared radiation. When incoming and outgoing energy are in balance, global temperature is relatively stable. Energy balance is crucial for sustaining conditions under which Earth’s inhabitants can thrive.

The term radiative forcing refers to changes in the net flow of energy (the net radiative flux) since 1750, the time of the Industrial Revolution, due to the effects of external drivers such as greenhouse gases that warm our planet and changes to features of our planet such as aerosols and ice cover that reflect the sun's incoming visible light, thus cooling our planet. Positive radiative forcing that warms our planet has accelerated greatly since the 1950s due to the increasing scale and rate of human activities.

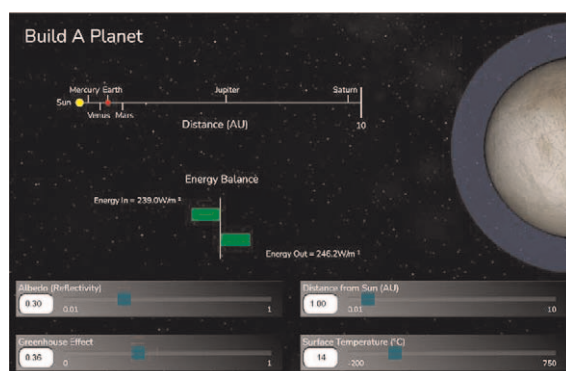
You and your students can engage with this activity set to visualize the factors that regulate Earth's radiative forcing, with a particular focus on the chemical substances produced by human activity that increase and decrease the energy retained by Earth. You can then explore how the Planetary Boundaries framework provides a systems perspective on those changes to the climate change Earth system process, and how climate change interacts dynamically with other Earth system processes.

Chemistry and sustainability connections: energy, electromagnetic spectrum, combustion reactions, aerosol formation, thermochemistry, reflection and absorption of light, phase changes of water, Earth's energy balance, climate change, Earth system interconnections, radiative forcing by greenhouse gases and aerosols and their effects on surface temperature, albedo of Earth's surface (reflectivity), positive and negative feedbacks.

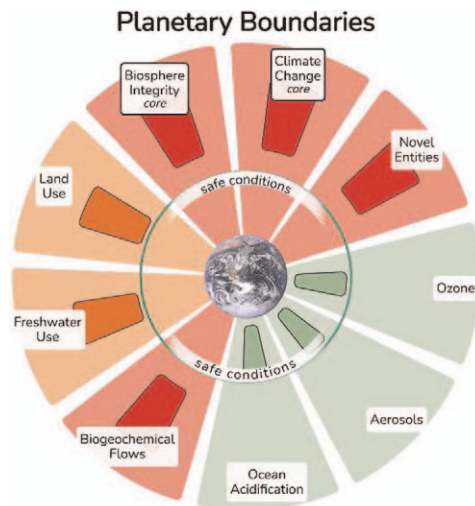
Interactive learning tools: this activity set uses two interactive learning tools:

KCVS Build a Planet Learning Tool:

<https://applets.kevs.ca/BuildAPlanet/buildAPlanet.html>



KCVS Planetary Boundaries Learning Tool:
<https://applets.kcvs.ca/PlanetaryBoundaries/>



Planetary boundaries connections:

- Climate Change Earth system process: Control Variable 2: Radiative forcing relative to 1750.
- Atmospheric Aerosol Loading: Control variable: Aerosol optical depth (AOD). Focus on the reflection of visible light from the sun back into space (the effects of aerosols on albedo).

Box 6.1 provides learning outcomes for the following activities to identify factors controlling Earth's energy balance.

Box 6.1 Learning outcomes for activities to identify factors controlling Earth's energy balance.

- Identify the factors that regulate Earth's energy balance.
- Define the term "radiative forcing" and illustrate, with examples, what is meant by "positive" and "negative" radiative forcing.
- Describe the role greenhouse gases and Earth's albedo each play in regulating surface temperature.
- Identify the Earth system processes in the Planetary Boundaries framework that help us understand climate change.
- Identify the control variables for the climate change Earth system process. Explain to a friend the concept of the planetary boundary

for that climate change Earth system process and identify its current level of risk.

- Describe the most important connections between the climate change Earth system process and each of the other Earth system processes in the Planetary Boundaries framework.

Activities:

- a. Explore the simplified model of planet Earth's energy balance in the KCVS Build a Planet learning tool (<https://applets.kcvs.ca/BuildAPlanet/buildAPlanet.html>) to identify the factors that determine the difference between incoming solar energy and the energy Earth radiates back into space. Which of the sliders cause more energy to be retained by Earth? Which cause less energy to be retained?
- b. In the same learning tool, set the greenhouse gas slider to zero and set the albedo (reflectivity) to the value in the planetary data table for Earth. Then adjust the average surface temperature slider so as to bring the energy coming in from the sun and radiating out from Earth to be about equal. What is the average surface temperature? Would you care to live on Earth if it had no greenhouse gases?
- c. In the same learning tool, set the albedo (reflectivity) and the average surface temperature to the values given in the planetary data table for Earth. Adjust the amount of greenhouse gases until the energy balance between incoming and outgoing energy is about equal. Now reduce the albedo by 10%. What happens to Earth's energy balance when the albedo is lowered? Bring the planet back into balance by adjusting the surface temperature. Did the Earth get cooler or warmer than the temperature you started with? What kinds of human activity might cause the albedo to go down?
- d. In the same learning tool, reset the albedo and average surface temperature for Earth to the values given in the planetary data table. What happens to Earth's energy balance if you now increase the amount of greenhouse gases? Bring the planet back into balance by adjusting the surface temperature. Did Earth get cooler or warmer? What kinds of human activity might cause the amount of greenhouse gases to go up?
- e. Now open the KCVS Planetary Boundaries Learning Tool (<https://applets.kcvs.ca/PlanetaryBoundaries/>). Click on the "show legend" button. What do the colors of each wedge represent? Which of the nine Earth system processes in the Planetary Boundaries framework are most closely related to the adjustments to Earth's energy balance you made by changing Earth's albedo and greenhouse gas

concentrations? What is the level of risk for the Earth system process(es) you identify? Use the play button on the time scale at the bottom to see how the level of risk for those Earth system processes has changed over the past 120 years. When did each reach its current level of risk?

- f. Now click on the *climate change* Earth system process. Note the two alternative control variables that determine the level of risk for climate change – the concentration of carbon dioxide in the atmosphere, and the radiative forcing at the top of Earth’s atmosphere compared to 1750. What units are used for each? What chemical substances do you think might influence the radiative forcing besides carbon dioxide?
- g. Finally, click on the *connections* tab at the top of the planetary boundaries learning tool, then select the climate change Earth system process. Write down what you consider to be the most important connection between climate change and each of ocean acidification, stratospheric ozone depletion, atmospheric aerosol loading, biogeochemical flows, novel entities, and biosphere integrity. Pick two of these connections you consider to be most important and explain how reducing the amount of carbon dioxide you produce each day might improve the change to the control variable for each of those Earth system processes.

6.3.3.2 *What Chemical Substances in the Atmosphere Have Caused the Greatest Change to Radiative Forcing Since the Industrial Revolution?*

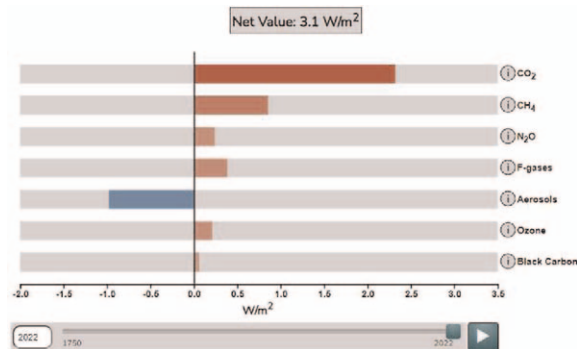
The activity set in Section 6.3.3.1 focused on Earth’s energy balance, the difference between energy coming in from the sun and the energy emitted by the Earth in the form of infrared radiation. Positive and negative radiative forcers were introduced – substances introduced into the atmosphere in greater amounts due to human activity that warm and cool our climate, respectively. In this second activity set you will explore the idea of radiative forcing more deeply, looking at data showing how radiative forcing has changed over time, and how much each of the key chemical substances in our atmosphere have contributed to increasing or decreasing radiative forcing since 1750.

Chemistry and sustainability connections: electromagnetic spectrum, absorption of IR radiation by greenhouse gases, sulfate aerosols, molecular structure and bonding, descriptive chemistry of main group elements, climate change mitigation, the role of greenhouse gases as positive radiative forcers and sulfate aerosols as negative radiative forcers, the importance of systems thinking in understanding climate change.

Interactive learning tools: this activity set uses two interactive learning tools:

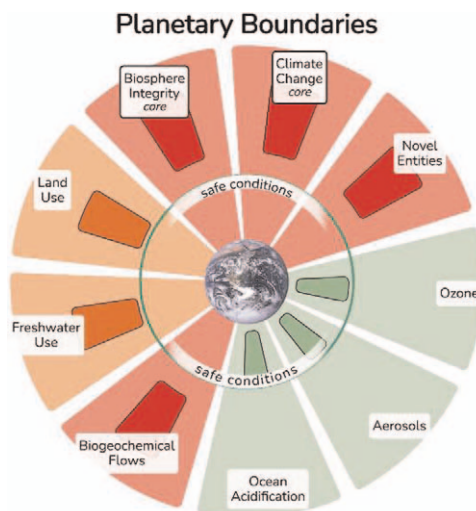
KCVS Radiative Forcing Learning Tool:

<https://www.kcvs.ca/details.html?cardName=radiativeForcing>



KCVS Planetary Boundaries Learning Tool:

<https://applets.kcvs.ca/PlanetaryBoundaries/>



Planetary boundaries connections:

- Climate Change Earth system process: Control Variable 2: Radiative forcing relative to 1750.
- Atmospheric Aerosol Loading: Control variable: Aerosol optical depth (AOD). Focus on the reflection of visible light from the sun back into space (albedo) by aerosols and other substances and phenomena.

Box 6.2 provides learning outcomes for understanding what chemical substances in the atmosphere have caused the greatest change to radiative forcing since the Industrial Revolution.

Box 6.2 Learning outcomes for understanding which chemical substances in the atmosphere have caused the greatest change to radiative forcing since the Industrial Revolution.

- Identify the key substances that drive changes to Earth's climate by absorbing infrared radiation in the atmosphere (positive radiative forcers) and by increasing Earth's albedo by reflecting visible light from the sun (negative radiative forcers).
- Evaluate the overall change-over-time behavior of radiative forcing since 1750.
- Evaluate the change-over-time behavior of the key positive and negative radiative forcers since 1750 and explain which substances have made the largest contributions to warming and cooling.
- Give an example of how reduction of a serious air pollutant led to unintended consequences for Earth's climate.
- Assess the potential benefits, harms, and unintended consequences of carrying out large-scale climate engineering by using sulfate aerosols to cancel out warming by greenhouse gases.
- Describe the interplay between the climate change Earth system process and the aerosol system in the Planetary Boundaries framework in regulating Earth's climate.

Activities:

- a. Open the KCVS Radiative Forcing Learning Tool (<https://www.kcvs.ca/details.html?cardName=radiativeForcing>). After reading the overview, explain to a classmate the connection between radiative forcing and climate change.
- b. In the same learning tool, using the slider under the graph, set the time to 1750. What is the value of radiative forcing for each of the substances shown? Why do you think the year 1750 was set as the starting point in understanding how human activity has changed radiative forcing?
- c. Now "play" the radiative forcing of our planet from 1750 to 2023 by using the play button at the bottom of the radiative forcing graph. What trend do you observe in the radiative forcing value over time?
- d. Look more closely at the change-over-time data. Write down the net value of radiative forcing on 7 dates: 1750, 1900, 1950, 1980, 2000, 2010, and 2020. Using a spreadsheet create a table of these dates and

- their radiative forcing values. Then putting the dates on the *x*-axis and the radiative forcing values on the *y*-axis, create a scatter plot of your data. How would you describe the shape of the curve that results? In which decades do you see the slope of the radiative forcing values start to change most rapidly? Using an internet search engine, look up what is meant by the term “The Great Acceleration”. Does your graph support the time period for this acceleration given in the source you found?
- e. Work through the five scenarios in the learning tool, each focused on one of the most important positive or negative radiative forcers. Can you describe any findings that were surprising to you about the substances that are the main drivers of climate change? Have you learned about their effects on radiative forcing in any of your chemistry classes?
 - f. Then open the KCVS Planetary Boundaries Learning Tool (<https://applets.kcvs.ca/PlanetaryBoundaries/>) and click on the climate change Earth system process. Consider each of the two control variables in turn. Why does the concentration of carbon dioxide in our atmosphere not tell the whole story of what drives climate change?
 - g. The second control variable in the Planetary Boundaries Learning Tool is radiative forcing (energy change per unit area of the globe since 1750, measured in W m^{-2}). Note the value of the control variable at the planetary boundary – the transition from a low risk to high risk level. When did that occur? How far above the safe conditions for radiative forcing are we today?
 - h. Returning to the KCVS Radiative Forcing Learning Tool (<https://applets.kcvs.ca/RadiativeForcing/index.html>), work through the case study on aerosols and bunker fuel. Explain to a classmate how reducing the amount of a serious pollutant in the atmosphere led to unintended impacts on Earth’s climate.
 - i. In light of what you have learned about positive and negative radiative forcers and the case study of sulfate aerosols, would you recommend that humans explore further the use of sulfate aerosols to limit the amount of warming by greenhouse gases? Write down the potential benefits, harms, and unknown consequences that you think politicians should consider.

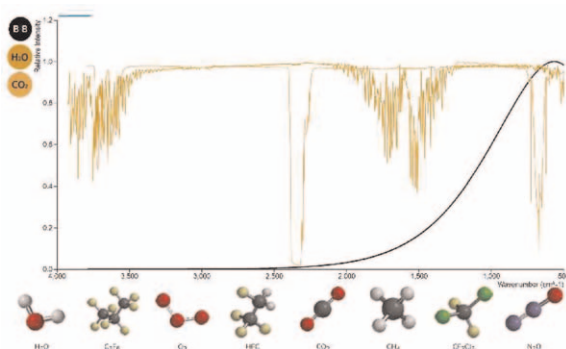
6.3.3.3 *What Makes a Chemical Substance an Important Greenhouse Gas?*

Having considered in Section 6.3.3.1 the factors that regulate Earth’s energy balance, and in Section 6.3.3.2, the substances that have caused the greatest change to radiative forcing since 1750, you can turn in this third activity set to looking more closely at what makes a substance a greenhouse gas. As illustrated with several of the most important greenhouse gases, the three factors to consider are (a) the atmospheric lifetime of a gas, (b) its concentration in the atmosphere, and (c) its infrared spectrum.

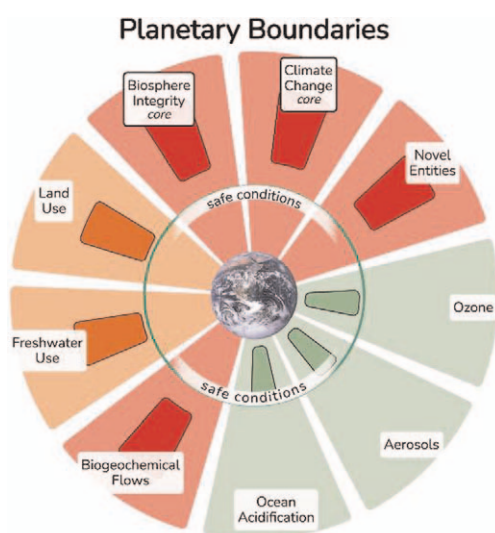
Chemistry and sustainability connections: structure–activity relationships, infrared spectroscopy, absorption of IR radiation by greenhouse gases, gas-phase reactions of pollutants in the troposphere, molecular structure and bonding, climate change mitigation, the role of greenhouse gases as positive radiative forcers, and atmospheric lifetime of gases.

Interactive learning tools: This activity set uses two interactive learning tools:

KCVS IR Windows for Greenhouse Gases Learning Tool:
<https://applets.kcvs.ca/IRWindows/IRWindows.html>



KCVS Planetary Boundaries Learning Tool:
<https://applets.kcvs.ca/PlanetaryBoundaries/>



Planetary boundaries connections:

- Climate Change Earth system process: Control Variable 2: Radiative forcing relative to 1750.

Box 6.3 provides learning outcomes for understanding what makes a chemical substance an important greenhouse gas.

Box 6.3 Learning outcomes for understanding what makes a chemical substance an important greenhouse gas.

- Identify the three factors that determine whether a substance released into the atmosphere will be a significant greenhouse gas, contributing to driving radiative forcing changes.
- Describe what is meant by the term “infrared spectral window”.
- Explain what molecular structure features of greenhouse gases determine the atmospheric lifetime of a gas.

Activities:

- a. Open the KCVS Visualizing the Chemistry of Climate Change (<https://vc3chem.com/index.html>) suite of interactive lessons and navigate to the module on gases and Key Idea 5: Greenhouse Gases (https://vc3chem.com/gases/G_5_1.html). List the three key factors that determine what makes a substance a significant greenhouse gas. Then identify the two most abundant gases in the Earth’s atmosphere. Are they greenhouse gases? Why or why not?
- b. Key Idea 5 describes the interaction between greenhouse gases and electromagnetic radiation. What region of the electromagnetic spectrum is absorbed by greenhouse gases?
- c. The *concentration of a gas* is the first factor important in determining whether a substance will be an important greenhouse gas. Referring back to the KCVS Radiative Forcing Learning Tool (<https://applets.kcvs.ca/RadiativeForcing/index.html>) that you used in the last activity set, what are the five most important greenhouse gases in changing Earth’s radiative forcing?
- d. Consider a puzzle. N_2O has a radiative forcing of about half that of CH_4 , despite the fact that the concentration of CH_4 is 6 times greater in the atmosphere. The primary reason is that CH_4 molecules have C–H bonds, and hydroxyl free radicals found in the atmosphere can readily react with CH_4 , breaking down CH_4 molecules into very reactive free radical fragments. This gives CH_4 a much shorter *atmospheric lifetime* than N_2O . N_2O molecules last longer in the atmosphere and can absorb more IR over their atmospheric lifetime than CH_4 molecules can.

- e. Consider a second puzzle. Compare the radiative forcing of N_2O to that of CO_2 in the KCVS Radiative Forcing Learning Tool (<https://applets.kcvs.ca/RadiativeForcing/index.html>). The atmospheric concentration of CO_2 is greater than that of N_2O by a factor of ~ 1000 , yet the radiative forcing of N_2O is about 25% that of CO_2 . The most important factor in this case is the differences in the infrared spectra of these two gases.
- f. Explore this second puzzle by opening the IR Window for Greenhouse Gases learning tool (<https://applets.kcvs.ca/IRWindows/IRWindows.html>). Under the “Display Options” button, select “Blackbody Curve”. The emission curve for Earth appears, showing you the wavenumbers at which Earth emits infrared radiation. Next, click on the image of a CO_2 molecule. You will see that CO_2 absorbs IR strongly right at the peak of Earth’s emission curve. This makes CO_2 such an important greenhouse gas. A second greenhouse gas that has been present in our atmosphere throughout the history of our planet is water vapor, H_2O . Click on the water molecule to display its IR spectrum alongside that of CO_2 . You will see that while CO_2 and H_2O absorb a substantial amount of the IR Earth is emitting, there are some flat lines on the top of the spectrum where these two important greenhouse gases do not absorb IR emitted by Earth. Click on N_2O , and its IR absorption spectrum appears – note that it absorbs in one of these regions in the IR spectrum where Earth emits IR, but CO_2 and H_2O do not have absorption peaks. We call this region of the IR, between about 700 and 1300 cm^{-1} , a “spectral window”. The IR that Earth emits in this window would escape the Earth’s atmosphere, cooling the planet, were it not for gases like N_2O that absorb in the IR spectral window region. As you saw earlier, the concentration of N_2O and other greenhouse gases that absorb in the IR spectral window have increased substantially since the Industrial Revolution and now trap increasing amounts of IR that would otherwise be escaping into space.
- g. Finally, open the KCVS Planetary Boundaries Learning Tool (<https://applets.kcvs.ca/PlanetaryBoundaries/>). Return to the consideration you gave in the activity in Section 6.3.3.2, part f, about why the second control variable for climate change in the Planetary Boundaries framework is important. If you want to predict whether a relatively new gas introduced by human activity, such as nitrogen trifluoride, NF_3 , used in the electronics industry, will contribute significantly to changing radiative forcing, what information would you need to know about its structure and properties to make an educated prediction?

Beyond these three activity sets, a comprehensive set of activities that connect climate change and the Planetary Boundaries framework to teaching and learning of chemistry at the undergraduate level has recently been published.²⁷

6.4 Closing Thoughts

Chemistry education, research, and practice need to consider the long-term, large-scale aspects of sustainability because chemical processes, both natural and human-caused, are fundamental to processes of Earth system change. Problems of unsustainability are increasingly recognized as urgent challenges, and calls are being made at the highest international levels for shifts in chemistry education so that learners are better equipped to respond to today's challenges for people and the planet.

This chapter has shown how the Planetary Boundaries framework can help to enrich curriculum development and place existing curriculum content in the context of today's interconnected Earth and societal systems. To fully realize the power of using the Planetary Boundaries framework to link chemistry teaching and learning to sustainability, exploration needs to go beyond simply identifying connections between chemistry topics and *individual* Earth system processes in the framework. The tools of systems thinking are particularly helpful here, and the KCVS Planetary Boundary Learning Tool provides an effective way to visualize system effects.

Climate change, the example used in Section 6.3, is a multi-faceted, complex system that is connected to each of the other eight biophysical Earth system processes in the Planetary Boundaries framework. This makes it a good starting point for bringing systems thinking into the learning process. As a “core” Earth system process in the Planetary Boundaries framework, if its control variables move substantially beyond their planetary boundaries, the climate change system has potential, on its own, and through coupled interactions with other Earth system processes, to drive the entire Earth system into a new and uncertain state. The three sets of activities we have outlined above can help equip chemistry educators to emphasize the importance of considering system-level properties of the entire Earth system. They can help students see how changes to a chemical parameter, like the concentration of CO₂ in our atmosphere or changes to radiative forcing, disrupt not only the climate system but multiple other Earth system processes, and the Earth system as a whole.

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References

1. E. Elhacham, L. Ben-Uri, J. Grozovski, Y. Bar-On and R. Milo, *Nature*, 2020, **588**, 1.
2. P. Friedlingstein, M. O'Sullivan, M. W. Jones, R. M. Andrew, L. Gregor and J. Hauck, *et al.*, *Earth Syst. Sci. Data*, 2022, **14**(11), 4811.
3. Z. Hausfather, The Climate Brink, <https://www.theclimatebrink.com/p/the-staggering-scale-of-human-co2> (accessed August 2025).
4. European Chemical Society, <https://www.euchems.eu/euchems-periodic-table/> (accessed August 2025).
5. J. Rockström, W. Steffen, K. Noone, Å. Persson, F. S. Chapin III, E. F. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, B. Nykvist, C. A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen and J. A. Foley, *Nature*, 2009, **461**, 472.
6. A. S. Downing, A. Bhowmik, D. Collste, S. E. Cornell, J. Donges and I. Fetzer, *et al.*, *Environ. Res. Lett.*, 2019, **14**(7), 073005.
7. W. Steffen, K. Richardson, J. Rockström, S. E. Cornell, L. Fetzer and E. M. Bennett, *et al.*, *Science*, 2015, **347**(6223), 1259855.
8. K. Richardson, W. Steffen, W. Lucht, J. Bendtsen, S. E. Cornell and J. F. Donges, *et al.*, *Sci. Adv.*, 2023, **9**(37), eadh2458.
9. C. Butz, J. Liechti, J. Bodin and S. E. Cornell, *Sustainability Sci.*, 2018, **13**(4), 1031.
10. D. Vanham, A. Leip, A. Gall, T. Kastner, M. Bruckner and A. Uwizeye, *et al.*, *Sci. Total Environ.*, 2019, **693**, 133642.
11. T. Häyhä, P. L. Lucas, D. P. van Vuuren, S. E. Cornell and H. Hoff, *Global Environ. Change*, 2016, **40**, 60.
12. European Union, Decision (EU) 2022/591 of the European Parliament and of the Council of 6 April 2022 on a General Union Environment Action Programme to 2030, Report No.: OJ L 114, 12.4.2022, 22, <http://data.europa.eu/eli/dec/2022/591/oj/eng> (accessed August 2025).
13. J. Rockström, W. Steffen, K. Noone, Å. Persson, F. S. Chapin III and E. Lambin, *et al.*, *Ecol. Soc.*, 2009, **14**, 1.
14. L. Persson, B. M. C. Almroth, C. D. Collins, S. E. Cornell, C. A. de Wit and M. L. Diamond, *et al.*, *Environ. Sci. Technol.*, 2022, **56**, 1510.
15. L. Wang-Erlandsson, A. Tobian, R. J. van der Ent, I. Fetzer, S. te Wierik, M. Porkka, *et al.*, *Nat. Rev. Earth Environ.*, 2022, **3**(6), 380.
16. R. P. MacDonald, A. N. Pattison, S. E. Cornell, A. K. Elgersma, S. N. Greidanus, S. N. Visser, M. Hoffmann and P. G. Mahaffy, *J. Chem. Educ.*, 2022, **99**(10), 3530.
17. P. G. Mahaffy, S. A. Matlin, T. A. Holme and J. MacKellar, *Nat. Sustainability*, 2019, **2**(5), 362.
18. A. R. Szozda, Z. Lalani, S. Behroozi, P. G. Mahaffy and A. B. Flynn, *J. Chem. Educ.*, 2024, **101**(6), 2290.

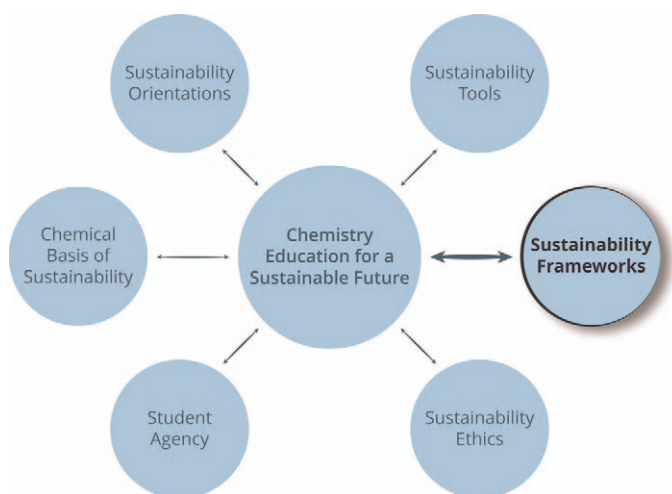
19. International Union of Pure & Applied Chemistry, Learning Objectives and Strategies for Infusing Systems Thinking into (Post)-Secondary General Chemistry Education, IUPAC Project No. 2017-010-1-050, <https://iupac.org/project/2017-010-1-050> (accessed August 2025).
20. P. G. Mahaffy, F. M. Ho, J. A. Haack and E. J. Brush, *J. Chem. Educ.*, 2019, **96**(12), 2679.
21. International Union of Pure & Applied Chemistry, Systems Thinking in Chemistry for Sustainability: Toward 2030 and Beyond (STCS 2030+), IUPAC Project No. 2020-014-3-050, <https://iupac.org/project/2020-014-3-050> (accessed August 2025).
22. A. R. Szozda, P. G. Mahaffy and A. B. Flynn, *J. Chem. Educ.*, 2023, **100**(5), 1763.
23. V. Talanquer, R. Bucat, R. Tasker and P. G. Mahaffy, *J. Chem. Educ.*, 2020, **97**(9), 2696.
24. National Research Council (NRC), The Next Generation Science Standards, The National Academies Press, Washington, DC, 2013.
25. National Oceanic and Atmospheric Administration (NOAA) Global Monitoring Laboratory, Trends in atmospheric carbon dioxide, <https://gml.noaa.gov/ccgg/trends/> (accessed August 2025).
26. P. M. Forster, C. Smith, T. Walsh, W. F. Lamb, R. Lamboll and B. Hall, *et al.*, *Earth Syst. Sci. Data*, 2024, **16**(6), 2625.
27. P. G. Mahaffy, J. Lunn, A. Adema, A. Ayotte, J. Faulkner and S. Greidanus, *et al.*, *J. Chem. Educ.*, 2024, **101**(9), 3856.

CHAPTER 7

Sustainability Frameworks II – UN Sustainable Development Goals[†]

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7.1 Opening Thoughts

In 2015, the United Nations (UN) set forth the Sustainable Development Goals (SDGs) as a pathway to a just, equitable, and sustainable future for people and the planet.¹ These 17 Goals (Figure 7.1) provide a call to action for scientists to be globally aware of the challenges facing people, prosperity, and the planet now and, critically, for a sustainable future. Study of the UN SDGs affords students an understanding and appreciation for the worldwide efforts in sustainable development and the essential role chemistry must play, in collaboration with other disciplines, to achieve these goals by the targeted year of 2030. This chapter explores how the UN SDGs provide chemistry educators with a wealth of teaching opportunities that can be scaffolded through all levels of curriculum with rich science and socio-scientific content to inspire and prepare learners to themselves contribute to a sustainable future for generations to come.

The importance of integrating the UN SDGs into the chemistry curriculum is summarized in the next three sections. Studies have shown that presenting chemistry topics in the context of real-world problems facilitates interest and learning for students. As students connect chemistry principles with the ability to help solve the complex challenges delineated by the SDGs, this can reinforce their understanding of the molecular basis for sustainability and build skills in systems thinking.²

As this chapter will illustrate, every sector of the chemical enterprise offers examples in which the UN SDGs and associated 169 targets are prominently



Figure 7.1 The 17 United Nations Sustainable Development Goals (UN SDGs).¹ Reproduced from ref. 1 with permission from the United Nations. The content of this publication has not been approved by the United Nations and does not reflect the views of the United Nations or its officials or Member States.

portrayed as a roadmap for sustainability. Thus, students must be able to demonstrate knowledge and literacy about the SDGs as they apply for positions in academia, industry, the private sector, or government.

Quality Education, **SDG 4**, speaks not only to quality and equitable education for all children, adults, and teachers, but also to the need for all learners to have the knowledge and skills to promote sustainable development through their careers, lifestyles, and actions. Education systems across the world increasingly are requiring and encouraging inclusion of the SDGs as a vital component of curricula.^{3,4}

7.1.1 Placing Chemistry in the Context of Sustainable Development

The Sustainable Development Goals place molecular-level science in the context of the broad picture of the needs of humanity and the environment. Studying individual SDGs can bring to light chemistry technologies necessary to achieve each goal. The goals also highlight the interdisciplinary efforts that will be required and encompass the social, economic, and environmental pillars of sustainability.

For example, **SDG 3**, “Ensure healthy lives and promote well-being for all at all ages”, necessitates the collaboration of chemists, biologists, food scientists, and health professionals to discover the essential nutrition and medicines needed to maintain good health, treat disease, and develop vaccines. Foundational courses are often comprised of students of these majors, especially pre-health professionals; therefore, discussions and/or assignments that involve the basic sciences’ contributions to “good health and well-being” can afford rich cross-disciplinary discussions for learners. The use of relevancy and socio-scientific issues by chemistry educators has been shown to engage and motivate students in the classroom.⁵

Another important sustainability topic is **SDG 6**, “Ensure availability and sustainable management of water and sanitation for all”. One in ten people on the planet do not have access to clean water.⁶ Analytical chemists are working with environmental scientists and engineers to identify contaminants and improve water purification methods as well as desalination technologies. In the laboratory and classroom, educators can tie instrumental techniques and chemical analyses to quantification of pollutants in the environment.⁷ Additionally, common chemical products in students’ daily lives such as pharmaceuticals, pesticides, and personal care products are now categorized as “contaminants of emerging concern”⁸ and detected in soil and water. Incorporating lecture and laboratory content integrating these topics with course learning outcomes reinforces chemistry’s connection to societal issues and the need for new strategies for pollution prevention. Media coverage on topics such as “forever chemicals” (see Chapter 3) and the Flint, Michigan water crisis are just two examples that present opportunities for learning chemistry within a context.

7.1.2 How Do the SDGs Help Prepare Students for Careers?

The chemical enterprise, including industry, academia, government, professional societies, non-profit organizations, and the public sector, is embracing the UN SDGs as inspiration for its sustainability efforts. Students who understand chemistry's role in achieving the SDGs will help all sectors of the chemical enterprise advance their sustainability objectives.

7.1.2.1 Chemical Industry

Many chemical companies promote their efforts toward achieving the UN SDGs through product development or initiatives within their companies.^{9,10} For example, two of the top three global chemical companies,¹¹ Dow Chemical Company¹² and BASF,¹³ define their sustainability efforts through association with the 2030 Goals. Both companies focus their sustainability efforts on Affordable and Clean Energy (SDG 7), Responsible Consumption and Production (SDG 12), and Climate Action (SDG 13). Dow Chemical's 2025 sustainability goals also include Good Health and Well-Being (SDG 3) and Industry, Innovation, and Infrastructure (SDG 9). BASF focuses on Zero Hunger (SDG 2), Gender Equity (SDG 5), Clean Water and Sanitation (SDG 6), and Decent Work and Economic Growth (SDG 8). Students familiar with the UN SDGs will be more apt to investigate a prospective employer's sustainability initiatives and be prepared to connect their skill set with the company's priorities and values.

In 2018, the World Business Council for Sustainable Development (WBCSD) published a "Chemical Sector SDG Roadmap" that describes the chemical industry's potential for contributing to the 2030 goals.¹⁴ The roadmap details the unique position of the chemical sector to advance technologies and address the goals in collaboration with other industrial sectors. The interactive website of the WBCSD provides a wealth of information on the chemical sector's interactions with all seventeen goals, case studies, and the potential impact opportunities for the industry to achieve the goals by 2030.¹⁵

The UN Environment Programme (UNEP) 2019 Global Chemicals Outlook II publication provides a worldwide view of the chemical enterprise's responsibilities for chemicals and waste management towards the goals. As illustrated in the report (Table 7.1), specific SDG targets that will be discussed later in the chapter are associated with ways in which chemistry could be used to minimize harm and provide solutions that have economic benefits.¹⁶ This searchable document is an exemplary resource covering the economic, social, and environmental dimensions of the chemistry discipline for sustainability. Chemistry educators should connect the dots from their courses to the Sustainable Development Goals to ensure that the next generation of chemical professionals acquires a sustainability mindset. Students with knowledge, understanding, and motivation towards these goals are likely to be attractive to the chemical industry as future employees.

Table 7.1 UNEP Table from the 2019 Global Chemicals Outlook II publication that connects various chemistry economic sectors to select UN SDG targets, demonstrating the breadth in opportunity for green and sustainable chemistry.¹⁵ Adapted from ref. 15 with permission from United Nations Environment Programme, 2019, per use for educational purposes.

Sectors	SDG targets	Examples of opportunities for management and innovation
Agriculture and food	 <p>2 ZERO HUNGER</p>	Target 2.4: sustainable food production Scale up Integrated Pest Management (IPM) and agroecological approaches, including development and use of non-chemical alternatives and other good agricultural practices
Health	 <p>3 GOOD HEALTH AND WELL-BEING</p>	Target 3.8: safe medicines and vaccines Sound management of pharmaceuticals and disinfectants that contribute to antimicrobial resistance
Energy	 <p>7 AFFORDABLE AND CLEAN ENERGY</p>	Target 7.a: clean energy research and technologies Improve technologies using resource-efficient, sustainable materials when decarbonizing the energy sector
Infrastructure	 <p>9 INDUSTRY, INNOVATION AND INFRASTRUCTURE</p>	Target 9.1: sustainable infrastructures Reduce raw material use and waste generation <i>via</i> advance materials without creating future legacies
Industry	 <p>9 INDUSTRY, INNOVATION AND INFRASTRUCTURE</p>	Target 9.2: sustainable industrialization Ensure that chemical-intensive industries rely on the best available techniques and best environmental practices

Table 7.1 (Continued)







Sectors	SDG targets	Examples of opportunities for management and innovation
Housing	 <p>11 SUSTAINABLE CITIES AND COMMUNITIES</p>	<p>Target 11.1: safe housing</p> <p>Reduce indoor air pollution through safer insulation and replace building materials of concern (e.g. asbestos)</p>
Transport	 <p>11 SUSTAINABLE CITIES AND COMMUNITIES</p>	<p>Target 11.2: sustainable transport systems</p> <p>Advance clean mobility, for example based on sustainable chemistry solutions for batteries</p>
Tourism	 <p>8 DECENT WORK AND ECONOMIC GROWTH</p>	<p>Target 8.9: sustainable tourism</p> <p>Adopt practices to reduce the chemical footprint of tourism services</p>
Mining	 <p>12 RESPONSIBLE CONSUMPTION AND PRODUCTION</p>	<p>Target 12.2: sustainable use of natural resources</p> <p>Ensure environmentally sound management of tailings</p>
Labor	 <p>8 DECENT WORK AND ECONOMIC GROWTH</p>	<p>Target 8.8: safe working environments</p> <p>Enhance risk assessment of chemicals of concern while promoting investment in green and sustainable chemistry to reduce hazardous occupational exposures</p>

Table 7.1 (Continued)

Sectors	SDG targets	Examples of opportunities for management and innovation
Education	 <p>4 QUALITY EDUCATION</p>	<p>Target 4.7: education for sustainable development</p> <p>Mainstream green and sustainable chemistry into relevant curricula</p>
Finance	 <p>17 PARTNERSHIPS FOR THE GOALS</p>	<p>Target 17.3: financial resources from multiple sources</p> <p>Enhance use of green and sustainable chemistry metrics as criteria in investment</p>

7.1.2.2 Academia

Colleges and universities across the world are placing a high priority on promoting their sustainability efforts through the SDGs. A recent analysis of peer-reviewed literature involving the integration of the UN SDGs into higher education from 2015 to 2021 reported an increase in publications since 2018, with the SDGs most frequently integrated into bachelor-degree programs.³ High-income countries were represented to a greater extent than low- and middle-income countries, potentially due to a lack of funding or awareness. A categorization of publications by discipline showed engineering/technology, humanities/social sciences, and business/administration/economics as most active in integrating the SDGs, respectively. Although chemistry was not listed in the top three disciplines, integrating the SDGs into chemical education is commonly an extension of content or placed in the context of teaching green chemistry principles and/or systems thinking. These topics are increasingly present in chemistry education publications.^{17,18}

As an example, consider The Association for the Advancement of Sustainability in Higher Education (AASHE), which has over 900 higher education institutions, businesses, and nonprofit members. AASHE uses the UN SDGs as part of its sustainability tracking, assessment, and rating system.¹⁹ The European University Association also publishes its commitment to the goals through research and education.²⁰ Additionally, higher education institutions are seeking the development of cross-disciplinary courses that address one or more of the goals through collaborative faculty efforts.^{21,22}

These types of initiatives allow chemistry students to see themselves as part of the equation for finding solutions.

7.1.3 Education is Key to Achieving the Sustainable Development Goals²³

Education is a central tenet of the Goals. Therefore, it is our responsibility as educators to “Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all (SDG 4)”. This charge is further detailed in Target 4.7 (Table 7.2).¹

A publication of the United Nations Educational, Scientific and Cultural Organization (UNESCO), *Education for Sustainable Development (ESD)* is a valuable resource for educators.²⁴ Though not specific to chemistry, the learning objectives it lays out can readily be adapted to chemistry and emphasize systems thinking as a core competency for achieving the goals. The document provides guidance to educators to empower their students to take personal action through participation and collaboration. Cognitive, socio-emotional, and behavioral learning objectives are defined for each of the seventeen goals along with suggestions for topics for classroom discussions and examples of instructional implementations. As illustrated in the next section, chemistry-related themes are present throughout the SDGs in the form of developing technological solutions and prevention of human and environmental harm.

Chemistry teachers need to help their students learn the skills needed to apply green chemistry principles and systems thinking practices to their areas of expertise in working towards the goals. From foundational courses to senior research projects, students can use the SDG framework to relate the basic sciences to environmental and health solutions. For example, nanotechnology advancements that address water purification or the design of biodegradable or compostable plastics to reduce plastics waste are topics primed for exploration in modern curricula.

In summary, inclusion of the UN SDGs throughout the chemistry curriculum will engage students, prepare them for a vast array of future careers, and contribute to advancing the sustainability goals. The remainder of this chapter focuses on additional resources available to teach the goals, various

Table 7.2 Target 4.7 under **SDG 4** calls for transformative education practices toward sustainable development. Icon reproduced from ref. 1 with permission from the United Nations.



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

educational modalities for incorporation, and specific examples for use in the laboratory and classroom.

7.2 Background

7.2.1 Chemistry and the SDGs

The UN SDG website¹ is an outstanding resource for instructors and students to collectively explore the 17 goals. Each goal has associated “targets” (169 total) with “indicators” (241) that define specific problems to address and metrics for evaluation of progress, respectively.

Some of the 17 goals connect more closely to chemistry than others. The targets reveal where the connections to chemistry are most evident. For example, **SDG 2** has the icon box title “No Hunger” and offers an expanded definition: “*End hunger, achieve food security and improved nutrition and promote sustainable agriculture*”. Eight targets are associated with the goal that, on the surface, may not appear to have a direct correlation to chemistry. However, Target 2.4 identifies contributions needed to meet this goal that are possible from chemists in the agricultural and environmental fields (see Table 7.3). Likewise, targets for SDGs 3, 6, 12, and 13 indicate chemistry-related technologies capable of addressing the sustainable development needed. Select targets frequently highlighted by chemistry educators are illustrated in Table 7.3.

7.2.2 Scaffolding the SDGs Across the Curriculum

Incorporating the sustainable development goals into the curriculum has the advantage that each educator can select content in their field of specialty to build a lesson plan they feel confident in teaching. Whether it involves the carbon cycle (see Chapter 1) and climate change, sustainable energy production, use of safe, renewable materials for health care products, determination of groundwater contaminants, biocatalysis using enzymes, or plastics in the ocean, an SDG exists that can be partnered with the chemistry concepts and/or technologies taught in lecture or laboratory courses.

Ideally, the UN SDGs would be scaffolded across a chemistry department’s courses to provide continuity and to emphasize their importance. This would require faculty coordination and buy-in. Table 7.4 lists commonly taught chemistry courses, a socio-environmental topic related to green/sustainable chemistry, and one (of many) SDGs that could be paired with the topic. This list is by no means exhaustive. For example, to highlight the sustainable future envisioned by the United Nations for *all* people, **SDG 5** (Gender Equality) and **SDG 10** (Reduced Inequalities) could be paired with each of these topics.

McNeil and co-authors verified the versatility of connecting the UN SDGs to the curriculum when they modified their entire first-year chemistry course with a UN SDG thematic framework.²⁵ They utilized active-learning activities

and case studies to connect course concepts such as gas laws, Lewis structures, bond energies, equilibrium, spectroscopy, molecular structures, and acid–base reactions to ten UN SDGs. Student feedback indicated that the SDG framework aided their learning of the course materials.

Table 7.3 Examples of SDG targets¹ pointing to chemistry-related solutions. Icons reproduced from ref. 1 with permission from the United Nations.

SDG goal	Select SDG targets pertaining to chemistry-related solutions
 <p>2 ZERO HUNGER</p>	<p>Target 2.4: By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, help maintain ecosystems, strengthen capacity for adaptation to climate change, extreme weather, drought, flooding, and other disasters and that progressively improve land and soil quality</p>
 <p>3 GOOD HEALTH AND WELL-BEING</p>	<p>Target 3.9: By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination</p> <p>Target 3.3: By 2030, end the epidemics of AIDS, tuberculosis, malaria and neglected tropical diseases and combat hepatitis, water-borne diseases and other communicable diseases</p>
 <p>6 CLEAN WATER AND SANITATION</p>	<p>Target 6.3: By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally</p>
 <p>12 RESPONSIBLE CONSUMPTION AND PRODUCTION</p>	<p>Target 12.4: By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water, and soil in order to minimize their adverse impacts on human health and the environment</p> <p>Target 12.5: By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse</p>
 <p>13 CLIMATE ACTION</p>	<p>Target 13.3: Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning</p>

Table 7.4 Sample socio-environmental and socio-scientific topics that overlap with course content and one (of many) possible related SDGs.

Course	Topic	Associated SDG (SDG#)
Foundational chemistry	Climate change	Climate Action (13)
Organic chemistry	Environmental impact of pharmaceutical production	Responsible Consumption and Production (12)
Analytical chemistry	Ground water contaminants	Clean Water and Sanitation (6)
Biochemistry	Biocatalysis with enzymes	Good Health and Well-Being (3)
Physical chemistry	Sustainable energy	Affordable and Clean Energy (7)
Inorganic chemistry	Earth-abundant/endangered metals	Life on Land (15)
Polymer science	Polymers/plastics in the ocean	Life Below Water (14)
Environmental chemistry	Separation technologies to minimize hazardous waste	Industry, Innovation, and Infrastructure (9)

7.2.3 Connecting Green Chemistry Principles, Systems Thinking, and the UN SDGs

Since the publication of the 12 principles of green chemistry by Anastas and Warner,²⁶ green chemistry educational materials have increased exponentially in the literature.²⁷ Although green chemistry and sustainable chemistry have differences,²⁸ the overall themes of pollution prevention and minimizing harm to people and the environment are shared by both. Recently, the chemistry education community recognized systems thinking (Chapter 4) as an effective strategy to teaching a holistic approach to practicing chemistry and assuring a truly sustainable outcome.

For foundational chemistry courses, the Haber-Bosch process has been used to illustrate the connections among chemistry concepts and the 2030 Goals. Mahaffy *et al.* presented a dynamic systems thinking approach that connects the learning outcomes of ammonia synthesis to subsystems including chemical inputs, energy and reaction requirements, the Ostwald process, intended uses, and environmental unintended consequences.² Two different System-Oriented Concept Map Extension (SOCME) diagrams were modeled to visualize the connectivity of the subsystems. The study set the stage for linking the reactive nitrogen cycle to five UN SDGs directly, and less directly to five additional UN SDGs.²⁹ Figure 7.2, similar to the graphic presented by Mahaffy *et al.*,²⁹ illustrates a classroom activity tasking students to draw interconnections between the use and production of nitrogen fertilizers with SDGs, both in advancing and preventing achievement of the goals. These types of activities will give students an appreciation for the complexity of anthropogenic chemicals that both benefit society and cause harm to the environment.

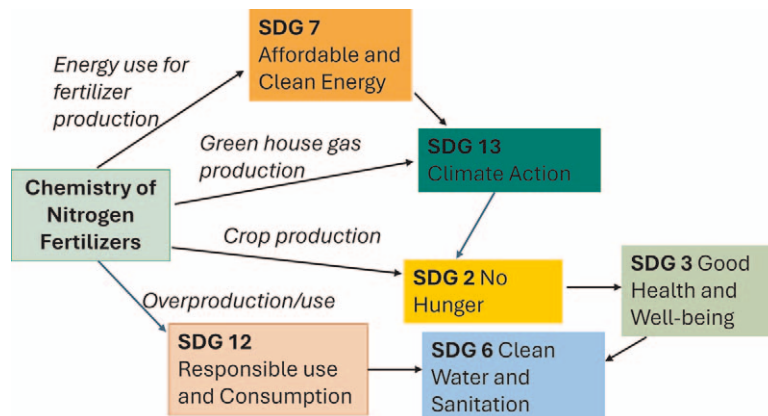


Figure 7.2 Representation of interconnections between production and use of nitrogen fertilizers and UN SDGs.

For upper-level courses in which students are beginning to identify their own areas of interest and expertise, a project-based learning opportunity may fit well. For example, students in an upper division green chemistry course at the University of Minnesota were required to select a current green-chemistry related sustainability topic of personal interest and write a term paper that reviewed state-of-the-art technologies in the field and innovations needed to address remaining challenges. Topics chosen by students included algae-based fuels, solar panels from earth abundant metals, phthalates as endocrine disruptors, reprocessing and storage of high-level nuclear waste, biomimetic adhesives, and biocatalysis in the pharmaceutical industry. Though not required, many students placed the theme of their paper into the context of sustainable development and the UN SDGs.³⁰ This assignment allowed students to build skills in scientific literature searching, to explore a topic of interest, to demonstrate their chemistry knowledge, and to provide broader social, economic, and environmental perspectives. Peer reviews from classmates were instrumental in exposing students to a variety of socio-environmental and socio-scientific challenges and opportunities for green and sustainable chemistry. Extensions to this assignment could include the required identification of specific UN SDGs targets and indicators, and mapping the connected UN SDGs, as illustrated in Figure 7.2.

Table 7.5 offers driving questions for various levels of student exploration of the SDGs. The driving questions encourage problem-based learning through provocative, open-ended questions with multiple solutions.³¹

D'eon and Silverman provide an example of connecting green chemistry principles and the UN SDGs with a teaching module on stoichiometry for introductory chemistry.³² A backwards design of learning outcomes using a SOCME³³ helped define system boundaries and objectives. The central topic of the module was the impacts of combustion. The authors connected reaction stoichiometry and efficiency with green chemistry principle

Table 7.5 Multi-level strategies for introducing the UN SDGs in curriculum through driving questions.

Instruction level	Driving question	Depth of chemistry discussion
1st year curriculum, non-science majors, or outreach	<i>How will chemistry/scientific disciplines be essential in achieving the SDGs?</i>	Broad, non-technical
Foundational	<i>What SDGs connect with “X” chemistry concepts we are learning?</i>	General, technical
2nd/3rd year curriculum	<i>Consider SDG “X” and propose how the chemistry and chemical technologies you are learning can contribute to this SDG – associate with specific targets and indicators.</i>	Applying technical skills
3rd/4th year curriculum and research	<i>Describe the relationship between sustainability topic X, your researched technology, and connections to applicable SDGs. What further innovations are needed to accomplish the SDGs and what are the current scientific/social/economic barriers?</i>	Technical and knowledge of broader chemical enterprise initiatives

#2 (atom economy), and the use of green metrics such as reaction mass efficiency. Students evaluated the efficiency of various combustion processes with **SDG 7** (Clean Energy) and **SDG 13** (Climate Action).

Hurst and co-authors demonstrated the integration of green chemistry, the UN SDGs, and systems thinking in a laboratory experiment involving valorization of spent coffee grounds.³⁴ Mitarlis, *et al.* sought to map the green chemistry principles taught in their basic science lecture and laboratory course with the SDGs.³⁵ The environmental pillar of sustainable development was identified as the connecting link between five green chemistry principles and addressing **SDG 12** and **SDG 13** objectives.

7.2.4 Chemistry Societies and Web-based Resources

Internationally, chemistry professional societies promote the SDGs and education towards the goals through their strategic initiatives and conferences. For example, the Campaign for a Sustainable Future of the American Chemical Society (ACS) places the UN SDGs at the center of the chemical enterprise’s potential to contribute through new technologies and innovations.³⁶ The International Union for Pure and Applied Chemistry (IUPAC) promotes green chemistry for the goals through its Interdivisional Committee for Green Chemistry for Sustainable Development, their projects, and activities.³⁷ During the IUPAC World Congress in July 2019, 16 leaders of

international chemical societies signed a Joint Framework that agreed to advance the SDGs through global partnerships. Since then, 24 additional chemical societies have become signatories.

The ACS Green Chemistry Institute has partnered with chemistry educators from over 45 institutions to develop “Green Chemistry Learning Modules” for general and organic chemistry courses. Each module focuses on core chemistry concepts through the lens of a systems thinking approach and identifies overlapping green chemistry principles, sustainability topics, and associated UN SDGs.³⁸ For example, one module introduces ideal gas laws in the context of the anthropogenic nitrogen cycle. Students construct SOCMEs to illustrate the nitrogen cycle as a system. SDGs that are relevant to the module are highlighted on the website.³⁹

In summary, for educators who have already embraced the inclusion of green chemistry and/or sustainability into their curriculum, the UN SDG framework together with the Planetary Boundaries Framework (Chapter 6) offer a natural and important extension for students’ understanding of the broader implications of scientific advancements.

7.3 Teaching & Learning the UN Sustainable Development Goals

7.3.1 Polymers, Plastics, and the UN SDGs

As illustrated in the previous section, an abundance of socio-environmental and socio-scientific topics can be explored in the context of the UN SDGs. This section features the topic of plastics, that is, *synthetic organic polymers*. Plastics both contribute to the quality of human life and cause harm to the planet and all living inhabitants. Their contributions are an undeniable success story of chemists and chemical engineers who can design a material to perform any function desired; however, microplastics now are so pervasive on earth that they are found in human blood.⁴⁰ Clearly the production and use of polymeric materials and plastics at the current rate is not sustainable, with current data showing we have exceeded their planetary boundaries limits.⁴¹

The chemistry curriculum can be enriched by adding information about the urgent and real-world problem of plastics pollution. Every student has seen media reports of sea turtles trapped in a six-pack plastic ring, expired seabirds filled with plastic bottle caps, seals trapped in fishing nets, plastic garbage littering our highways, or the great garbage patches floating in our oceans. Plastics offer a platform for instructors to teach important chemical concepts together with the design of new materials without the unintended negative environmental consequences.

7.3.2 Polymer Basics

The instruction of polymer science in higher education varies around the world as to when and at what level it is taught. Presented here is one

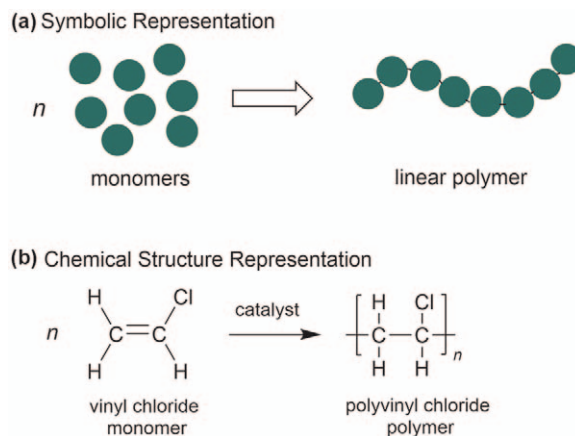


Figure 7.3 Different representations of the conversion of monomers to linear polymer chains: (a) symbolic representation, and (b) chemical structure representation.

approach, primarily from the perspective of an organic chemist, rather than a comprehensive study of polymer science. In addition, additives such as plasticizers, colorants, and stabilizers are omitted for brevity.

For foundational courses, polymers are often represented by symbol-based formulas (Figure 7.3a), and for organic chemistry courses and above, by full line angle formulas (Figure 7.3b). At all levels, the concept of covalently bonded repeating units and the large size (molecular mass) of the resulting polymer is important. The repeating units for the chemical representations are placed in brackets with “*n*” representing the number of repeating units. For example, a typical value of “*n*” for commercial polyvinyl chloride (PVC) is approximately 1300, giving a molecular mass of $80\,000\text{ g mol}^{-1}$ or 80 kg mol^{-1} (Figure 7.3b).

Polymers can also have different architectures (Figure 7.4). Linear synthetic polymers and copolymers (more than one type of polymer in the chain, for example block copolymers) are generally classified as thermoplastics and can be softened when heated and reshaped when cooled. These types of polymers are typically recyclable. In contrast, traditional cross-linked polymers and networked polymers are difficult to melt, undergo a chemical change when heated, and cannot be reformed. These types of plastic materials are generally not recyclable.⁴²

Polymers can be classified by their method of synthesis. Chain-growth (addition) polymers and step-growth (condensation) polymers are often taught in the context of a laboratory experiment or in studying atomic or molecular species or mechanisms. For example, most first-year and organic chemistry courses introduce free radicals and/or free radical mechanisms, which is an opportune time to connect to free radical polymerizations used for producing polyethylene and polystyrene. Polymerizations can also occur under cationic and anionic reaction

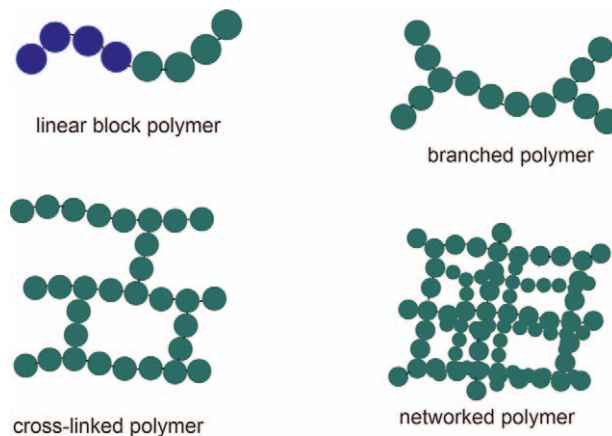


Figure 7.4 Different polymer architectures.

conditions. *Each instructor should consider the specific learning outcomes associated with their experiment or course content in deciding the breadth of polymer synthesis coverage.*

If time permits, presenting a brief history of the development of plastics emphasizes how rapidly chemists and chemical engineers produced plastics with almost any imaginable property, *e.g.*, soft, flexible, absorbent, hard, durable, or resistant to corrosion. Large scale production of polyvinyl chloride began in 1927, and polystyrene was invented in 1930 and nylon in 1938. The year 1950 saw the mass production of plastics reach 2 million metric tons and marked the start of the proposed Anthropocene geological age in which human activity gained dominance over Earth's climate and environment changes.⁴² Excellent resources are available for sharing the exponential growth of the plastics industry and the urgent need to reconsider society's approach to use and production.⁴³

7.3.3 Activity Set #1. The Benefits and Problems with Using Plastics

Undoubtedly, connections exist among the benefits of polymers/plastics, the unintended negative environmental consequences of polymers/plastics, and the UN SDGs. Therefore, this first classroom activity (Box 7.1) asks students to identify the contributions of plastics to the quality and longevity of human life and then associate them with their ability to advance specific UN SDGs and SDG targets. This activity is appropriate for all levels and could augment a lecture or laboratory module on polymer chemistry for more advanced students.

The activity can be implemented as a "brain-storming session" or as one that requires student documentation of specific examples with/without references. Student responses may include recognizing plastics as critical to medical care in providing life-saving health measures through the

Box 7.1 Classroom Activity #1: Recognizing the benefits and problems associated with plastics.

Activity Set #1:

- a. What benefits do plastics provide to human life expectancy and society?
- b. What human health and environmental problems have developed from their prolific use in society?
- c. What UN SDGs (and targets) can be associated with each benefit and problem listed?

prevention of infection and spread of disease (**SDG 3**). Students may also recognize that light-weight plastic materials contribute to affordable, clean wind and solar energy, as well as the design of energy efficient vehicles (**SDG 7**). Finally, students may note that plastic packaging is needed to keep perishable food fresh during delivery to non-local markets and prevent foodborne illnesses and spoilage (**SDG 2**).

The next step in the activity asks students to identify the unintended consequences of anthropogenic plastics to human health and the planet and again connect to individual SDGs and targets. Plastic debris in the oceans is specifically called out in **SDG 14** where indicator 14.1.1b calls for reduction and monitoring of plastic debris in the ocean (Table 7.6).⁴⁴

For reference, a recent review of the current use, production, consumption, and management of microplastics and plastics identified specific challenges to achieving *twelve* of the UN SDGs.⁴⁴ For example, the presence of microplastics in food (**SDG 2**) and drinking water⁴⁵ (**SDG 6**) are of growing concern, and the release of greenhouse gases through the production cycle of plastics, recycling, and waste management, including incineration, contribute to climate change⁴⁶ (**SDG 13**). The upward trajectory of global plastic production is not sustainable and is not aligned with responsible consumption and production (**SDG 12**). Single-use plastics, low recycling rates (less than ~10%), and a throw-away mentality place human behavior at the core of these challenges (Figure 7.5).^{43,47}

Table 7.6 UN SDG Indicator 14.1.1b specifying the need to monitor plastic debris in the ocean. Icon reproduced from ref. 1 with permission from the United Nations.



SDG 14: Conserve and sustainably use the oceans, seas and marine resources for sustainable development

Target 14.1 By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution

Indicator 14.1.1b plastic debris density

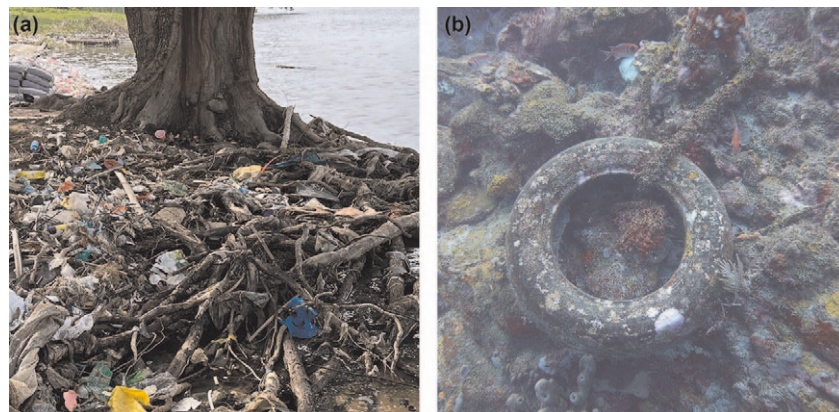


Figure 7.5 Plastic pollution on land and in water as a result of our throw-away society. Original photos by the author.

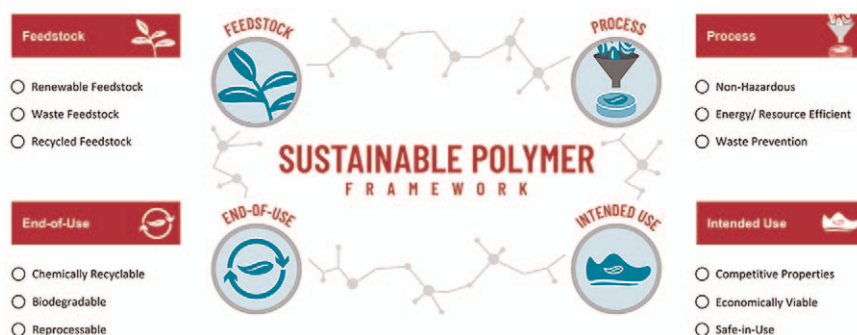


Figure 7.6 Sustainable Polymer Framework (SPF) for the design of new environmentally friendly polymeric materials.⁴⁹ Reproduced from ref. 49 with permission from American Chemical Society, Copyright 2022.

7.3.4 Activity Set #2. Designing More Sustainable Plastics for Meeting the SDGs

From Activity #1, students will recognize the complexity of the plastics problem, opening the door for them to ask: *How can scientists design new plastics that retain their benefits to society but minimize their harm?* This question emphasizes the importance of a systems thinking approach to developing new technologies in contrast to traditional material design solely for function (reductionist approach) without consideration of the life cycle and economic circularity of polymers.⁴⁸

What should a scientist consider when designing a new polymeric material? Figure 7.6 models one approach used by researchers at the National Science Foundation Center for Sustainable Polymers, where the origin of the

feedstock, polymerization process, intended use, and end-of-use are all considered through the lens of sustainability and systems thinking.^{49,50} The Sustainable Polymer Framework (SPF) has both interconnections among the four pillars and external subsystems interactions. Interconnection examples include use of *waste feedstock* that could originate from a *chemically recycled* product or derived from waste/by-product of a *process*, promoting a circular economy model. External subsystem examples include evaluation of water, energy, and environmental impacts in using renewable biomass or in developing a new process applying green chemistry principles. One application of the graphic, as will be proposed in Activity Set #3, is to have students fill in the circles that apply to their sustainable polymer laboratory experiment or course assignment.

The UN Environment Programme offers an alternative graphic that reinforces the circularity of design and a life-cycle approach to plastics pollution (Figure 7.7).⁵¹ This type of graphic, of which there are many examples on the internet, is useful for discussing the unsustainable linear economy of plastics: make, use, and discard. Both Figure 7.6 and 7.7 provide students with an understanding of the holistic approach needed in developing a sustainable material and opportunities for innovative technologies needed to achieve the SDGs.

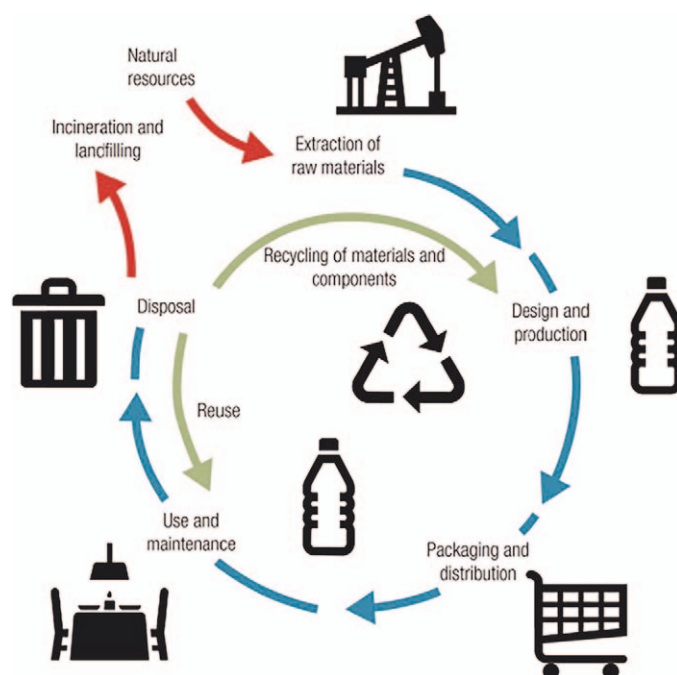


Figure 7.7 UNEP representation of a life-cycle approach to address plastic pollution. Reproduced from ref. 51 with permission from the United Nations Environment Programme, 2019, for use for educational purposes.

Box 7.2 Classroom Activity #2: Understanding plastics design for material and economic circularity to address plastics pollution and the 2030 goals.

Activity Set #2:

- a. Why did plastic design only for function result in the current situation of plastics pollution?
- b. What are the stages in the life cycle of a plastic to consider when designing a more sustainable plastic?
- c. What external systems connect to the life cycle of a plastic product and how can a systems design improve sustainability?

Classroom activity #2 (Box 7.2) partners the concepts of lifecycle considerations and systems interactions to identify points of pollution prevention and where alternative approaches to standard practices could reduce the environmental impact of a plastic material. Additionally, evaluation of the interconnected subsystems for each step in design (from feedstock to end-of-life) can introduce points of discussion and comparisons for contrasting plastics.

7.3.5 Activity Set #3. Single-use Packaging and the UN SDGs








Through the lens of systems thinking and sustainability, this activity asks students to compare three contrasting (*e.g.*, different feedstock, functionality, properties) commercial (bio)plastics. Students study their structure and properties, so they are knowledgeable and able to connect core chemistry principles to physical and mechanical properties. A single-use product or packaging, optionally made from one of the three studied plastics, is then chosen and its sustainability profile is assessed using the SPF graphic. Finally, social, economic, and environmental factors of the plastic product are related to the SDGs. An overview of learning goals for Activity Set #3 is given in Box 7.3.

Most likely, students are first introduced to plastics through the plastic resin codes (Table 7.7)⁵² and the campaign to “reduce, reuse, and recycle”. These codes identify the type of resin (unprocessed bulk plastic) used to make packaging and products and are imprinted on a plastic commercial product. The public misconception may exist that a code indicates a product can be recycled because of the similarity between the triangular circling arrows and the universal recycling symbol that uses a Möbius loop of arrows (Figure 7.8).⁵³ This is not necessarily true. Each municipality is responsible for informing its customers which plastic resin code materials will be collected and industrially recycled. The numbering of the resin codes does, however, indicate the ease of recycling with “1” being easiest to recycle and “6” and “7” most difficult. Consumers are then responsible for recycling materials according to their recycling vendor’s specifications.

Box 7.3 Student Learning Outcomes for activity Set #3.

- Learn the chemical structures of three contrasting plastic resins.
- Apply knowledge of molecular structure, chemical bond stability, and functional group reactivity to understand resulting properties related to applications and recyclability.
- Identify a single-use commercial packaging or product made from a polymer/plastic resin.
- Use the Sustainable Polymer Framework to identify sustainability attributes of the commercial application.
- Analyze potential pathways for the fate of the plastic and the impact on achieving the SDGs.

Table 7.7 Plastic resin identification codes.

Image							
Abbreviation	PETE	HDPE	PVC	LDPE	PP	PS	Other
Polymer name	Polyethylene terephthalate	High-density polyethylene	Polyvinyl chloride	Low-density polyethylene	Polypropylene	Polystyrene	Other

**Figure 7.8** Universal recycle symbol.⁵³ Reproduced from ref. 53 with permission.

The next student activity focuses on the most collected and recycled resin, poly(ethylene terephthalate) (PETE) (resin code 1); the less recycled polymer, low-density poly(ethylene) (LDPE) (resin code 4); and the bioplastic, poly(lactic acid) (PLA) (resin code 7). PETE and LDPE are derived from

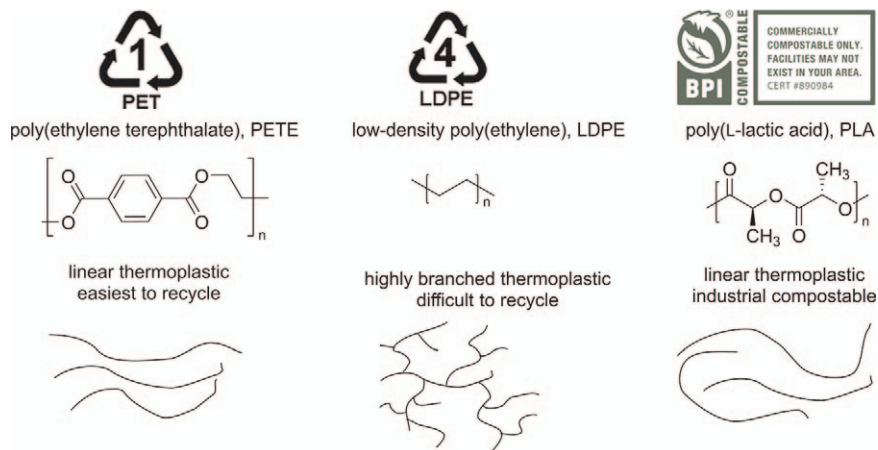


Figure 7.9 Structures and end-of-life management codes for PETE, LDPE, and PLA, three contrasting plastics to explore in Activity #3.

petroleum, an established, inexpensive, but depleting feedstock. PLA is derived from bio-based carbohydrate feedstocks such as corn, wheat, or sugar beet (first generation) or agricultural waste such as corn stover, wheat straw, and food waste (second generation).⁵⁴

An instructor could choose other petroleum-based plastics from the resin codes and/or alternative biobased plastics derived from starch, cellulose, lignin, algae, or chitosan.⁵⁵ Additionally, wholly or partially biobased polymers such as PET (bio-PET) or polyethylene (bio-PE) could be explored. To place the lesson in context, consider using examples relevant to regional recycling practices, agriculture, and industry. As an illustration, a country known for coffee production or large consumption of coffee could explore current efforts to valorize spent coffee grounds for biopolymers and composite production.^{34,56,57} The bio-based feedstocks may be particularly interesting for biochemistry curriculum when biomolecules are taught.

Step-by-step implementation of Activity #3 is outlined in the text that follows. The exercise progresses from basic polymer concepts to considerations of the life cycle of a commercial single-use plastic and culminates in making connections to specific SDGs.

Instructor Introduction to the Activity: present three contrasting plastic resins as modeled in Figure 7.9 at the level appropriate for the course. Groups can work cooperatively on all three plastic resins or be assigned different plastic resins to investigate and then share their data with the whole class. In this way, each student gains an understanding of the unique properties of three plastic resins.

Student Task #1: find a representative molecular mass for each type of polymer and determine the number of repeating units, “*n*”. Report in

kg mol^{-1} . Chemical catalogs or Safety Data Sheets are useful resources for these data using a CAS number.

- **Instructor Note:** *For upper-level courses, find literature melting and glass transition temperatures for the polymers.*

Student Task #2: what type of functional groups and bonds are present in each polymer? Based on functional groups, which polymer resin would be most resistant to aqueous acidic or basic hydrolysis? How might the branching of LDPE affect the crystallinity of the material? Provide a rationale for why PLA is more easily hydrolyzed than PETE.

- **Instructor Note:** *simple aqueous hydrolysis was used to consider degradability since different methods for recycling and composting quickly become complex.*
- **Instructor Note:** *the main goal is for students to recognize that LDPE contains unreactive, hydrophobic C–C bonds, whereas PLA and PETE contain ester bonds that are more hydrolysable. The branching in LDPE prevents ordered chains and van der Waals interactions, thus decreasing crystallinity (this can be contrasted to high-density polyethylene). PETE is less reactive than PLA under aqueous conditions due to the hydrophobicity of the aromatic rings and steric effects. For advanced courses, a stronger argument is the higher glass transition temperature of PETE than that of PLA.*

Student Task #3: identify a single-use consumer packaging or product produced from each plastic resin and characterize its properties (e.g., hard, flexible, transparent, opaque, colored, soft, stretchy)

- **Instructor Note:** *have students pick a range of different packaging/products (that is, not all beverage bottles).*
 - **PETE**⁵⁸ is used for plastic bottles, salad domes, peanut butter containers, mouthwash bottles, vegetable oil containers [generally tough, durable, resistant to heat, solvents, and acids and bases, can be microwaved, good oxygen barrier].
 - **LDPE** is used for plastic bags, squeezable bottles, plastic gloves, six-pack rings for soda cans, tubing [flexible, transparent, moisture resistance – *low glass transition temperature correlates with low crystallinity and amorphous properties*].
 - **PLA** is the most successful commercial bioplastic on the market.⁵⁹ Many university campuses and sports arenas use PLA cups, cutlery, and food containers, which are designed to be collected and disposed of in industrial composting facilities. PLA filament is now popular for use with desktop 3D printing and PLA blends are used for medical implants, sutures, drug delivery and automobile parts⁶⁰ [PLA is brittle and lacks “toughness” for applications where deformation is required].

Student Task #4: select one single-use plastic packaging or product from step 3 or as directed by your instructor to study. Consider, perhaps, the first discarded plastic you find outdoors, packaging found in an item delivered to your dwelling, or a new “sustainable product” from the internet, and have it approved by the instructor.

Student Task #5: complete two versions of the SPF graphic to indicate: (a) sustainable attributes of the plastic item at each life cycle stage, and (b) possible challenges that may exist when considering human behavior and interactions with subsystems connected to each life cycle stage.

Student Task #6: construct a table that connects the information on your graphic to four SDGs, explaining whether the single-use item is a challenge to or contributes to achieving each goal.

- **Instructor Note:** *unless the assignment is directly based on a laboratory experiment or literature publication, the processing used to make the packing/product can be difficult for students to find directly, and allowing generalizations such as “established infrastructure”, “energy intensive”, “drop-in replacement”, or other may be appropriate.*

Two examples of graphics that students might produce related to a commercially available PLA compostable fork are illustrated in Figures 7.10 and 7.11 based on literature precedence.^{54,59–61} Figure 7.10 identifies characteristics of the PLA fork that meet sustainable polymer criteria, whereas, Figure 7.11 presents potential challenges to meeting the criteria related to consideration of interactions with connected subsystems and human behavior. The exercise could be completed with other graphical tools^{33,62} or life-cycle graphics depending on the emphasis and depth of learning outcomes desired.

A table connecting the life cycle of a PLA compostable fork with the UN SDGs is illustrated in Table 7.8. Again, graphical representations could also be used to represent the interconnections, both direct and indirect.

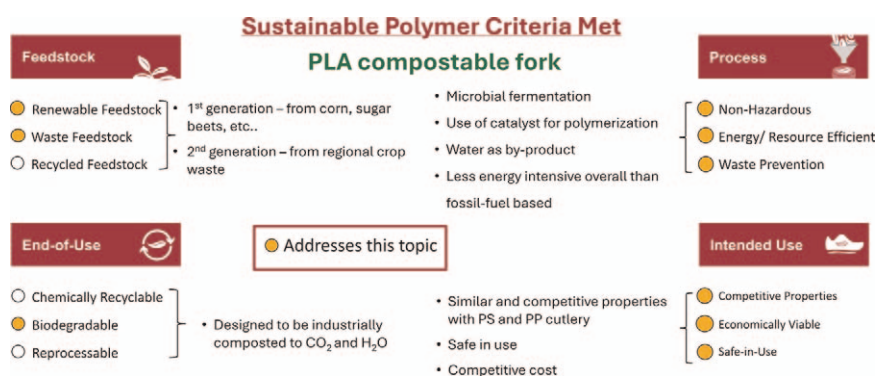


Figure 7.10 Sustainable polymer characteristics of a PLA compostable fork.

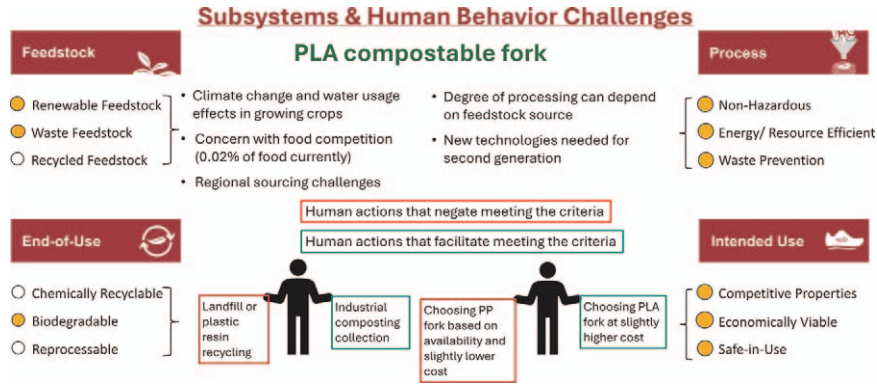






Figure 7.11 Subsystem connections and human behavior challenges to meeting sustainability criteria for a PLA compostable fork.

Table 7.8 Sample connections of a PLA compostable fork and the UN SDGs. Icon reproduced from ref. 1 with permission from the United Nations.

SDG goal	Relationship to PLA plastic fork production, use, and disposal
 <p>12 RESPONSIBLE CONSUMPTION AND PRODUCTION</p>	Both consumers and companies could consider choosing PLA (especially second-generation materials) for use. Consumers can frequent businesses that prioritize use of sustainable materials like PLA and participate in responsible collection for industrial composting.
 <p>13 CLIMATE ACTION</p>	Though it can be controversial, much of the current research shows that the use of biomass such as that used for the PLA fork produces fewer greenhouse gases than petroleum-based polymers. Of course, responsible composting is necessary and avoiding disposal of product in methane-producing landfills is important.
 <p>11 SUSTAINABLE CITIES AND COMMUNITIES</p>	A PLA fork is only responsibly disposed of IF cities and communities make it a priority to have the appropriate infrastructure and facilities to collect PLA products and compost them. Some sports arenas use only PLA cups/cutlery, which is a good model.
 <p>3 GOOD HEALTH AND WELL-BEING</p>	The PLA fork is a safe, single-use plastic that, if disposed of appropriately, advances good health without detriment to the environment. However, if disposed of improperly and breaks down to microplastics, it may pose toxicity to organisms.

Box 7.4 Classroom Activity #3: Exploration of three plastic resins and a single-use consumer packaging/product for sustainability considerations and a broader UN SDG context.

Activity Set #3:

- a. What are the polymeric structures of three contrasting plastics and what role does structure play in their resulting properties and applications as well as end-of-life potential?
- b. For a given single-use (bio)plastic, what sustainability criteria are met assuming end-of-use design is followed?
- c. For a given single-use (bio)plastic, what challenges are introduced by consideration of connected subsystems, human behavior, or government policies?
- d. What positive and adverse impacts can the single-use plastic item studied have on specific UN SDGs?

With the abundance of resources available on the topic of plastics, chemistry teachers have the opportunity to both teach chemistry concepts in the context of polymers at course appropriate levels and engage students with one of the greatest global sustainability challenges of modern society. A summary of Activity #3 (Box 7.4) illustrates these motivations that the author hopes instructors find compelling to adapt.

7.4 Concluding Thoughts

The UN Sustainable Development Goals are both simple and complex. Introducing a graphical representation of the 17 goals (Figure 7.1) in foundational chemistry courses builds bridges between students of different majors and interests, especially if the SDGs have been introduced in non-chemistry courses. The SDGs offer opportunities for conversation in the classroom and at the dinner table: “*In chemistry class today we learned about the United Nation’s seventeen goals for a sustainable future. Clean water is one we discussed. . .*”

Connecting chemistry concepts to health and well-being (SDG 3), climate change (SDG 13), protection of the land (SDGs 2 and 15) and water (SDGs 6 and 14), affordable energy (SDG 7), and responsible industry and production (SDGs 9 and 12) provides context for solving problems that have local, regional, and world-wide implications. For chemistry educators, promoting and teaching the skills required for their students to contribute to sustainable development is concretely charged in SDG target 4.7. It is both a privilege and responsibility to prepare chemistry students not only with the technical knowledge to benefit both society and the environment but also with a sense of purpose and pride in their chosen career.

Box 7.5 Summary of learning outcomes connecting chemistry curriculum to the UN SDGs.

Students should be able to:

- a. Describe the overarching vision of the UN SDGs as providing a framework to achieve prosperity, equity, and health for all people and the planet.
- b. Know that the 17 SDGs have defined targets.
- c. Understand chemists' roles and responsibility to apply their scientific knowledge and skills to both prevent harm from chemical substances and seek solutions to address select SDGs and targets.
- d. Connect their chemistry knowledge to specific UN SDGs for both potential benefit and/or avoiding negative consequences.

What expectations should a chemistry educator have with respect to student knowledge of the UN SDGs? Certainly not memorizing the seventeen goals. Rather, an understanding of their purpose as a call to action for all people of the world “*to promote prosperity while protecting the planet*”.⁶³ Although the UN SDG targets encompass economic and social responsibilities of cities, regions, and countries, the charges for climate action and protection of the Earth's environment can only be fully realized through scientific advances. Student recognition that chemistry has a critical role to play in achieving and monitoring progress towards the goals is of paramount importance regardless of the level of instruction.

For chemistry majors, learning outcomes (Box 7.5) should include the ability to connect course specific chemistry concepts, green chemistry principles, analytical skills, and systems thinking strategies to the framework provided through the 2030 Agenda for Sustainable Development.⁶⁴ Scaffolding of the UN SDGs throughout the curriculum will bring students with interests in all areas of chemistry into the fold of the interdisciplinary collaborative efforts needed for a sustainable future.

Visibility of the UN Sustainable Development Goals continues to increase across all sectors of society along with the urgency to double efforts to advance them. The 2023 UN SDGs progress report presents a gloomy picture of unprecedented global warming and a concerning lack of progress towards these goals.⁶⁵ As Meriadoc Brandybuck from the “Lord of the Rings: Two Towers” movie poses to Treebeard, “*But you're part of this world! Aren't you?*” Though not a direct quote from J. R. R. Tolkien's book, it represents the warning Tolkien gave in the 1950s through his novels about the impending harm to the environment from the industrial revolution. We all are part of this world and as citizens and chemists we must act now for the universal good. Incorporating the UN SDGs across chemistry curricula to advance sustainability is one means to this end.

References

1. United Nations Department of Economic and Social Affairs, Sustainable Development, <https://sdgs.un.org/goals> (accessed August 2025).
2. P. G. Mahaffy, S. A. Matlin, J. M. Whalen and T. A. Holme, *J. Chem. Educ.*, 2019, **96**, 2730.
3. Á. Amorós Molina, D. Helldén, T. Alfvén, M. Niemi, K. Leander, H. Nordenstedt, C. Rehn, R. Ndejjo, R. Wanyenze and O. Biermann, *Global Health Action*, 2023, **16**, 2190649.
4. UNESCO, Education for sustainable development: a roadmap, <https://unesdoc.unesco.org/ark:/48223/pf0000374802> (accessed August 2025).
5. A. George, C. Zowada, I. Eilks and O. Gulacar, *Educ. Sci.*, 2021, **11**, 13.
6. S Omer, Global water crisis: Facts, FAQs, and how to help, <https://www.worldvision.org/clean-water-news-stories/global-water-crisis-facts> (accessed August 2025).
7. A. P. Dicks, *Green Anal. Chem.*, 2023, **7**, 100082.
8. US Environmental Protection Agency, Contaminants of Emerging Concern including Pharmaceuticals and Personal Care Products, <https://www.epa.gov/wqc/contaminants-emerging-concern-including-pharmaceuticals-and-personal-care-products> (accessed August 2025).
9. World Business Council for Sustainable Development, Leading chemical companies and industry associations chart a course towards collaboratively maximizing potential to contribute to the realization of the Sustainable Development Goals (SDGs), <https://archive.wbcsd.org/Programs/People-and-Society/Sustainable-Development-Goals/News/Leading-chemical-companies-and-industry-associations-contribute-to-the-realization-of-the-SDGs> (accessed August 2025).
10. S. Axon and D. James, *Curr. Opin. Green Sustainable Chem.*, 2018, **13**, 140.
11. A. H. Tullo, C&EN's Global Top 50 chemical firms for 2022, <https://cen.acs.org/business/finance/CENs-Global-Top-50-2022/100/i26> (accessed August 2025).
12. DOW, 2019 Sustainability Report Case Study, Aligning to the United Nations Sustainable Development Goals, <https://corporate.dow.com/en-us/seek-together/2019-sustainability-report-case-study.html> (accessed August 2025).
13. BASF, UN Sustainable Development Goals, <https://www.basf.com/global/en/who-we-are/sustainability/secure-long-term-economic-growth/networks/global-compact/goals> (accessed August 2025).
14. World Business Council for Sustainable Development (WBCSD), Chemical Sector SDG Roadmap, <https://www.wbcsd.org/resources/chemical-sector-sdg-roadmap/> (accessed August 2025).
15. The Chemical Sector | Sector SDG Roadmaps, <https://sdgroadmaps.wbcsd.org/the-chemical-sector/#section-chemSecSDGs> (accessed August 2025).
16. UN Environment Programme, Global Chemicals Outlook II: From Legacies to Innovative Solutions, Part V, p. 644, <https://www.unep.org/>

- resources/report/global-chemicals-outlook-ii-legacies-innovative-solutions (accessed August 2025).
17. J. J. MacKellar, D. J. C. Constable, M. M. Kirchhoff, J. E. Hutchison and E. Beckman, *J. Chem. Educ.*, 2020, **97**, 2104.
 18. P. G. Mahaffy, F. M. Ho, J. A. Haack and E. J. Brush, *J. Chem. Educ.*, 2019, **96**, 2679.
 19. STARS Aligned, Using the Sustainability Tracking Assessment & Rating System to Report on Contributions to the U.N. Sustainable Development Goals, <https://www.aashe.org/wp-content/uploads/2020/05/STARS-SDGs-May-26.pdf> (accessed August 2025).
 20. European University Association, Sustainable Development Goals, <https://www.eua.eu/publications/briefings/universities-and-sustainable-development-towards-the-global-goals.html> (accessed August 2025).
 21. S. Strachan, L. Logan, D. Willison, R. Bain, J. Roberts, I. Mitchell and R. Yarr, *Emerald Open Res.*, 2021, **3**, 24.
 22. A. Horn, A. Scheffelaar, E. Urias and M. B. M. Zweekhorst, *Int. J. Sustainability Higher Educ.*, 2023, **24**, 1.
 23. P. Anastas, M. Nolasco, F. Kerton, M. Kirchhoff, P. Licence, T. Pradeep, B. Subramaniam and A. Moores, *ACS Sustainable Chem. Eng.*, 2021, **9**, 8015.
 24. UNESCO, *Education for Sustainable Development: learning objectives*, UNESCO Digital Library, <https://unesdoc.unesco.org/ark:/48223/pf0000247444> (accessed August 2025).
 25. R. J. Petillion, T. K. Freeman and W. S. McNeil, *J. Chem. Educ.*, 2019, **96**, 2845.
 26. P. T. Anastas and J. C. Warner, *Green Chemistry: Theory and Practice*, Oxford University Press, New York, 1998.
 27. K. B. Aubrecht, M. Bourgeois, E. J. Brush, J. MacKellar and J. E. Wissinger, *J. Chem. Educ.*, 2019, **96**, 2872.
 28. V. G. Zuin, I. Eilks, M. Elshami and K. Kümmerer, *Green Chem.*, 2021, **23**, 1594.
 29. P. G. Mahaffy, S. A. Matlin, T. A. Holme and J. MacKellar, *Nat. Sustainability*, 2019, **2**, 362.
 30. J. Wissinger, unpublished work.
 31. S. Nagarajan and T. Overton, *J. Chem. Educ.*, 2019, **96**, 2901.
 32. J. D'eon and J. R. Silverman, *Green Chem. Lett. Rev.*, 2023, **16**, 2185109.
 33. K. B. Aubrecht, Y. J. Dori, T. A. Holme, R. Lavi, S. A. Matlin, M. Orgill and H. Skaza-Acosta, *J. Chem. Educ.*, 2019, **96**, 2888.
 34. L. I. Austen, T. I. J. Dugmore, A. S. Matharu and G. A. Hurst, *J. Chem. Educ.*, 2023, **100**, 327.
 35. M. Mitarlis, U. Azizah and B. Yonata, *J. Technol. Sci. Educ.*, 2023, **13**, 22.
 36. American Chemical Society, The ACS Campaign for a Sustainable Future Strategic Initiative, <https://www.acs.org/about/strategic-initiatives/acs-campaign-for-a-sustainable-future-strategic-initiative.html> (accessed August 2025).

37. P. Tundo and J. Wissinger, *Chem. Int.*, 2022, **44**, 35–37.
38. American Chemical Society, Green Chemistry Institute: Green Chemistry Learning Modules, <https://www.acs.org/green-chemistry-sustainability/education/teaching-modules.html> (accessed August 2025).
39. American Chemical Society, Green Chemistry Institute: The Anthropogenic N₂ cycle: Gas Phase Reactions Essential to Food and Life, <https://www.acs.org/green-chemistry-sustainability/education/teaching-modules/ideal-gases.html> (accessed August 2025).
40. H. A. Leslie, M. J. M. van Velzen, S. H. Brandsma, A. D. Vethaak, J. J. Garcia-Vallejo and M. H. Lamoree, *Environ. Int.*, 2022, **163**, 107199.
41. L. Persson, B. M. Carney Almroth, C. D. Collins, S. Cornell, C. A. de Wit, M. L. Diamond, P. Fantke, M. Hassellöv, M. MacLeod, M. W. Ryberg, P. Søggaard Jørgensen, P. Villarrubia-Gómez, Z. Wang and M. Z. Hauschild, *Environ. Sci. Technol.*, 2022, **56**, 1510.
42. R. Geyer, in *Plastic Waste and Recycling*, ed. T. M. Letcher, Academic Press, 2020, pp. 13–32.
43. Ellen MacArthur Foundation, The New Plastics Economy: Rethinking the future of plastics, <https://www.ellenmacarthurfoundation.org/the-new-plastics-economy-catalysing-action> (accessed August 2025).
44. T. R. Walker, *Curr. Opin. Green Sustainable Chem.*, 2021, **30**, 100497.
45. M. Kosuth, S. A. Mason and E. V. Wattenberg, *PLoS One*, 2018, **13**, e0194970.
46. S. Sharma, V. Sharma and S. Chatterjee, *Sci. Total Environ.*, 2023, **875**, 162627.
47. L. T. Sin and B. S. Tueen, *Plastics and Sustainability: Practical Approaches*, Elsevier, Amsterdam, Netherlands, 2023.
48. P. T. Anastas, *Trends Chem.*, 2019, **1**, 145.
49. F. M. Haque, J. S. A. Ishibashi, C. A. L. Lidston, H. Shao, F. S. Bates, A. B. Chang, G. W. Coates, C. J. Cramer, P. J. Dauenhauer, W. R. Dichtel, C. J. Ellison, E. A. Gormong, L. S. Hamachi, T. R. Hoyer, M. Jin, J. A. Kalow, H. J. Kim, G. Kumar, C. J. LaSalle, S. Liffland, B. M. Lipinski, Y. Pang, R. Parveen, X. Peng, Y. Popowski, E. A. Prebhalo, Y. Reddi, T. M. Reineke, D. T. Sheppard, J. L. Swartz, W. B. Tolman, B. Vlasisavljevich, J. Wissinger, S. Xu and M. A. Hillmyer, *Chem. Rev.*, 2022, **122**, 6322.
50. J. E. Wissinger, C. J. Ellison, W. R. Dichtel, A. B. Chang, J. T. Trotta, A. B. Yang and C. W. Bunyard, *Journal*, 2020, Sustainable Polymer Framework. Retrieved from the University Digital Conservancy, <https://hdl.handle.net/11299/211643>, (accessed August 2025).
51. UN Environment Programme: How can a life-cycle approach curb the plastic pollution crisis?, <http://www.unep.org/news-and-stories/story/how-can-life-cycle-approach-curb-plastic-pollution-crisis> (accessed August 2025).
52. Genpak Product Managers: Get To Know The Recycling Numbers 1 Through 7, <https://www.genpak.com/environment/knowning-your-plastics-recycling-symbols-no-1-to-7/> (accessed August 2025).

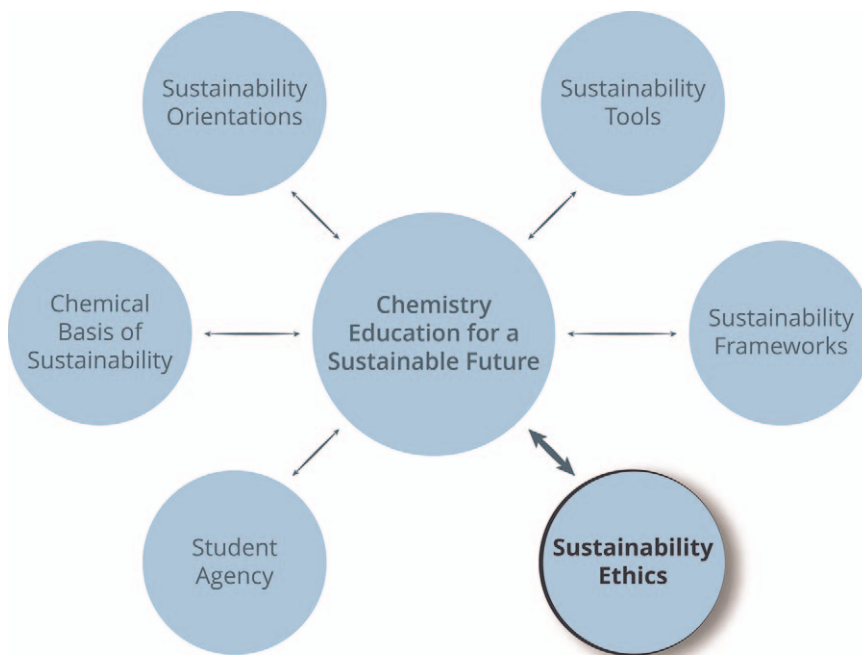
53. Wikipedia: Recycling symbol, https://en.wikipedia.org/wiki/Recycling_symbol (accessed August 025).
54. A. Abdelshafy, A. Hermann, S. Herres-Pawlis and G. Walther, *Global Challenges*, 2023, 7, 2200218.
55. A. Di Bartolo, G. Infurna and N. T. Dintcheva, *Polymers*, 2021, 13, 1229.
56. A. S. C. d Bomfim, D. M. d Oliveira, H. J. C. Voorwald, K. C. C. dC. Benini, M.-J. Dumont and D. Rodrigue, *Polymers*, 2022, 14, 437.
57. BeaNused®, Sustainable plastics made a reality from coffee grounds, <https://beanused.com/> (accessed August 2025).
58. R. Nisticò, *Polym. Test.*, 2020, 90, 106707.
59. S. Farah, D. G. Anderson and R. Langer, *Adv. Drug Delivery Rev.*, 2016, 107, 367.
60. W. Ali, H. Ali, S. Gillani, P. Zinck and S. Souissi, *Environ. Chem. Lett.*, 2023, 21, 1761.
61. N. Singh, O. A. Ogunseitan, M. H. Wong and Y. Tang, *Sustainable Horiz.*, 2022, 2, 100016.
62. Tools for systems thinking Archives – SaStice, <https://sastice.com/category/tools-for-systems-thinking/> (accessed August 2025).
63. United Nations Sustainable Development Goals: Home, <https://www.un.org/sustainabledevelopment/> (accessed August 2025).
64. Transforming our world: the 2030 Agenda for Sustainable Development | Department of Economic and Social Affairs, <https://sdgs.un.org/2030agenda> (accessed August 2025).
65. UN Sustainable Development Goals: Progress Chart, 2023, <https://unstats.un.org/sdgs/report/2023/progress-chart/Progress-Chart-2023.pdf> (accessed August 2025).

CHAPTER 8

Sustainability, Ethics, and Students[†]

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8.1 Opening Thoughts

Sustainable development is one of the great challenges of the 21st century. In 1989, this concept was first widely introduced to the world through the report *Our Common Future* prepared by the World Commission on Environment and Development.¹ The authors offered what has become the best-known definition: “Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. The report also points out that this definition includes two key concepts: (1) the needs of the poor around the world must be prioritized, and (2) there are limitations on how the environment can meet present and future needs.

What contributions can chemistry make to meeting the needs of the world, particularly for those people most in need? Several thoughtful reflections have been published in recent years that outline the positive impact of chemistry in the past and its potential to continue doing so.^{2–7} Starting in 2016, these and similar publications often make explicit connections to the United Nations (UN) Sustainable Development Goals (SDGs). The SDGs were adopted by the UN as a core part of the 2030 Agenda for Sustainable Development that seeks to achieve peace and prosperity for all people on Earth as well as the planet itself. The contributions of chemistry to accomplishing the SDGs, highlighted in other chapters in this book, reflect its unique combination of the ability to synthesize new materials with desired properties as well as the ability to measure and characterize a wide range of molecules. These same essays and reports also point out some of the problematic and negative impacts of chemistry, particularly regarding environmental degradation.

Chemists, like other scientists, have become accustomed to confronting ethical questions involving issues of fabrication, falsification, plagiarism, negligence, or conflicts of interest. Under the overall heading of “responsible conduct of research”,^{8,9} examination of these issues has been part of graduate education for many years and has also become a widespread part of undergraduate education. The appropriate ethical standards are clear, and there is often a single best answer to any scenario.

In contrast, decisions and actions related to using chemistry to achieve some component of the SDGs are more complicated and ambiguous. Jan Mehlich, the author of *Good Chemistry: Methodological, Ethical, and Social Dimensions*, has a Ph.D. in organic chemistry, an M.S. in applied ethics, and works at the Center for Life Science Ethics in Bonn. He comments: “what exactly is understood as a risk or benefit is the subject of endless debate and conflict”.¹⁰ The initial response of some chemistry educators may be to say that these situations are too complex and that chemistry instructors do not have the expertise in ethics to incorporate these societal applications into chemistry courses. However, Mehlich continues “A good chemist is the one who doesn’t back off from this perhaps more difficult question, but who engages with the multitude of stakeholders to figure it out by sharing the strengths of

chemistry – creating the material means to provide a higher life quality – and connecting it with the discourse on values, needs and demands”.¹⁰ To develop “good chemists” in the way Mehlich describes will require that we incorporate into our courses ethical aspects of chemistry applications related to sustainability and the SDGs. The goals of this chapter are to offer thoughts and provide practical examples as to how chemistry educators might approach this challenge, as well as to point to some useful resources.

8.2 Background

This section presents information on professional ethics, describes ways sustainability can be used to bring professional ethics into the college chemistry curriculum, and concludes with a set of helpful resources for teaching.

8.2.1 Professional Ethics

In the context of connecting chemistry applications to sustainability, professional ethics, in contrast to philosophical ethics, are relevant. Unlike ethical theories that form the heart of the philosophical field of ethics, professional ethics are a form of applied ethics that are not universal and thus can vary based on the occupation.

The work of Gardner and Shulman helps us understand how chemistry functions as a profession. In their approach, a profession consists of a group of individuals that society grants “a certain amount of prestige and autonomy in return for performing for society a set of services in a disinterested way”.¹¹ Members of a profession share “a commitment to serving others, either individual clients or society in general”. Gardner and Shulman point out that “The primary feature of any profession – the commitment to serve responsibly, selflessly, and wisely – sets the terms of the compact between the profession and the society”.¹¹ They see this commitment as essential to defining the ethical relationship between members of a profession and the general society that the profession is part of and serves. The centrality of this commitment defines the inherently ethical relationship between the professional and the general society.

Gardner and Shulman outline a set of characteristics shared by members of the same profession that allow them to serve others:¹¹

- a body of special knowledge that contains principles supportive of the ongoing development of the profession,
- a specialized set of skills and practices that are unique to that profession,
- the ability to render judgments characterized by integrity under conditions characterized by uncertainty (either technical or ethical), and
- the ability to learn from experience (individually or collectively) so that new knowledge is obtained in the context of professional practice.

These characteristics clearly apply to chemistry. The special knowledge and skills that characterize the profession of chemistry include synthesis of molecules, characterization of their interactions with each other, and measurement of amounts. Gardner and Shulman identify one final characteristic of a profession that applies to chemistry: a professional community provides oversight and monitoring of professional practice and education in the profession.¹¹ It is the professional community that bears the primary responsibility for articulating and communicating the ethical framework that should characterize the work of members of the profession.

Professional ethics are closely related to the unique responsibilities of each specific profession. Lawyers do not have the same knowledge and skills as doctors or chemists, and each group serves the larger society in very different ways. As a result, the codes of ethics developed and utilized by different professions may differ significantly. The relationships among these ethical codes and the legal systems in various countries can also vary significantly. Ethical codes for chemists include those developed by professional societies such as the American Chemical Society (ACS)¹² and the Royal Society of Chemistry,¹³ as well as others such as the Hague Guidelines¹⁴ and the Global Chemists' Code of Ethics¹⁵ that are written for an international audience.

Professional ethics can be viewed as having two dimensions, one "internal" oriented towards other members of the same profession and one "external" oriented towards the larger society. Concerns addressed by the "internal" dimension include allocation of credit, research misconduct, and appropriate actions in professional venues for communicating experimental work (publications and presentations). The "external" dimension is represented by statements regarding the handling of chemical waste and concerns for the public interest, including practicing chemistry in a way that benefits human health and the environment. Readers interested in exploring in more depth the internal and external aspects of chemistry's professional ethics are encouraged to read the work of Kovac¹⁶ and Mehlich.¹⁰

Building on Gardner and Shulman's description of professions, Sullivan and colleagues described three distinct dimensions that characterize professional education.^{17,18} The first is a cognitive dimension ("the head") focused on mastering the content and cognitive skills (*e.g.*, problem solving) that characterize how members of the profession think. The second is a skills dimension ("the hand") focused on mastering the specific skills (*e.g.*, using instrumentation, carrying out chemical reactions, calculation of reagent amounts) that members of the profession routinely use. The third is an ethical dimension ("the heart") focused on helping an individual develop the appropriate understanding of the ethical responsibilities that accompany membership in a particular profession. In the words of Colby and Sullivan, the ethical dimension of professional education serves to "...capture students' induction into the field's ethical standards and practices, professional sensibilities, appreciation for and commitment to the field's essential social purposes, and sense of professional identity in which

those purposes and standards are experienced as core features of what it means to practice that profession”.¹⁸

8.2.2 Ways to Bring Professional Ethics into the Chemistry Curriculum

Ethics is concerned with relationships and how we ought to see our connections to the other parties (human and nonhuman) in those relationships.¹⁹ In other words, incorporation of ethics into chemistry courses provides opportunities to have students think about the relationships connecting the chemistry being examined and the larger contexts in which the chemistry will be used. Incorporating ethics also engages students in thinking about the responsibilities they will have as chemists to help the larger chemistry community contribute to sustainable development.

Incorporating ethics related to sustainability into chemistry courses can be accomplished in several ways. The next section describes two of these: (1) a sustainability-related context, and (2) a case study or module.

8.2.2.1 Contexts to Teach Ethics

One way to engage students with ethical aspects of chemistry related to sustainable development is to design a course such that these issues are an integral part of the “narrative arc” of the course. This was the approach taken by SENCER, a systemic reform program launched in 2001 that was funded in part by the National Science Foundation.²⁰ SENCER stands for Science Education for New Civic Engagements and Responsibilities. SENCER courses start with complex civic issues and engage students in learning science “through” these issues.²¹

A representation of this approach is shown in Figure 8.1. The innermost circle represents disciplinary knowledge, in this case, the topic of Lewis structures in the discipline of chemistry. In a chemistry course, one might expect the instructor to take a position at the center of the circle. From this instructional vantage point, the instructor would first focus on the topic of Lewis structures and then reach “out” from the center to a real-world example or two. In contrast, the SENCER approach positions the instructor in a real-world issue at the edge of the circle. The instructor starts with the need for refrigerants to preserve food and, as chemical content is needed, reaches “into” the circle of foundational chemical concepts related to shapes of molecules and Lewis structures. Positioned at the edge of the circle, the instructor may reach into other circles as well, such as one for an ethical concept or one for the UN SDGs. The approach represented in Figure 8.1 will be presented in more detail in Section 8.3.2.

Since the launch of SENCER in 2001, several courses in STEM disciplines have been recognized as SENCER model courses,²² and a closer examination of these can help interested instructors develop a better understanding of

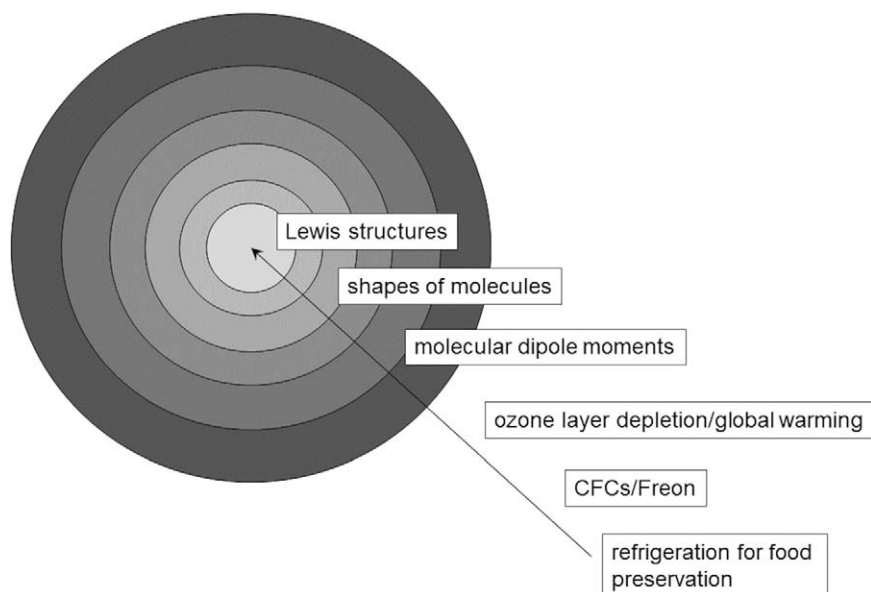


Figure 8.1 A representation of how a real-world issue can lead to exploration and learning of chemistry concepts. The SENCER approach positions the instructor in this real-world issue at the edge of the circle.

this approach. An example that connects aspects of the SDGs to upper-level biochemistry has been developed by this author and is described in more detail in other publications.^{23–26}

Outside of SENCER, other examples of chemistry courses exist in which instructors have connected chemistry content to issues related to sustainability and topics of the UN SDGs. Many of these involve an approach similar to the one described by Marks and Eilks,²⁷ in which socio-scientific issues are incorporated into chemistry courses to create opportunities for discussion and individual reflection and decision making.

For example, Caspers and Roberts-Kirchhoff describe a course they created for biochemistry majors that centers on recent advances in biochemistry and their relationship to social issues.²⁸ Topics examined in the course included drugs of abuse and HIV therapy, both the focus of specific targets within SDG 3, “Ensure healthy lives and promote well-being for all at all ages”.²⁹ Students presented papers to the entire class as a starting point for discussion that included ethical issues and societal concerns. At the end of the course, student teams presented a “dialogue paper” on a topic of their choosing that incorporated both scientific and ethical/social aspects.

A second example can be found in the work of McClure and Lucius, who describe a one-semester course they developed at the University of Alabama at Birmingham focused on chemical ethics and civic responsibility.³⁰ The class was offered as a chemistry elective that met once a week for two hours. Topics examined in the course included toxic waste sites such as Love Canal,

green chemistry, nanotechnology, and biodiesel/biofuels. Students in the course wrote a term paper on a scientific topic of public concern for which the paper included both a review of relevant scientific literature as well as a presentation of the student's opinion on the topic.

A third example is an interdisciplinary graduate course on solar energy described by Pullen and Brinkert.³¹ The course, taught in Sweden over a three-week period, involved a combination of readings and lectures by invited experts from different universities, industry, and nongovernmental institutions. Lectures were followed by discussion sessions that incorporated small group problem-based discussion, short role plays, and a laboratory exercise. Module topics included international renewable energy policies, economical and ethical aspects of energy consumption, applied solar research (focused on solar cells), industrial aspects, and current research topics in solar energy.

8.2.2.2 Case Studies and Modules to Teach Ethics

Another way to incorporate connections between sustainability and ethics in a chemistry course is by using modules or case studies for a small number of class meetings. Modules are a set of linked activities that can be implemented together within a course to accomplish one or more learning outcomes. From this perspective, case studies are a type of module deeply grounded in a particular set of real-world experiences. Either one can serve as a useful way of incorporating an ethics component into a class without redesigning the entire course.

Rowe describes an activity used in a nonscience majors course to introduce students to the basic science underlying the CRISPR technique for modifying nucleic acids, as well as social and ethical considerations related to the technology.³² Working in small groups, students research a particular topic related to CRISPR, with topics relating to various aspects of the technology (technical, social, ethical). Each group prepares short written and oral summaries that serve as the basis for a class discussion facilitated by the instructor. While CRISPR technology does not automatically connect to sustainability or the SDGs, Rowe's work provides a template that chemistry educators could easily adapt to design similar activities focused on a sustainability related topic in either introductory or advanced undergraduate courses.

Blonder *et al.* describe a module on the chemistry of lead developed for use with high school students in Israel.³³ The module is part of a larger project on responsible use and innovation that created materials for use in several different countries. In this 4.5-hour module, students are engaged in a variety of activities, including:

- introductory lectures on the characteristics of lead and a history of its use;
- a video focused on Clair Patterson, a geochemist who fought against lead as an additive in gasoline; and
- student discussions focused on dimensions of responsible research and innovation and applying those dimensions to the story of lead.

While the module as described is not explicitly focused on sustainability, it provides a template that chemistry educators can use to develop similar modules.

Ryno and Cottine describe a two-week team-taught interdisciplinary module that was used simultaneously in both an advanced biochemistry and an environmental ethics course.³⁴ The module focuses on the mechanism of pesticides and the ethics of using them domestically and in agriculture to explore the question of how understanding the chemistry of various pesticides and their impact on biological systems might shape preservation and conservation practices. Students are asked to complete a research paper on a pesticide of their choice to demonstrate their knowledge of the pesticide's mechanism of action and the ethics of using it.

Buckley and Fahrenkrug describe a case study on the water crisis in Flint, Michigan that they developed for an analytical chemistry course.³⁵ The case study consists of six complementary modules: (1) an introductory guided discussion of water, power, and privilege in Flint, (2) an in-class guided inquiry exercise designed to introduce the chemical concepts important to understanding the water crisis, (3) a laboratory analysis of real Flint water samples, (4) an exercise focused on statistical data validation, (5) software-based chemical equilibrium modeling, and (6) communication of scientific work and recommendations to non-scientists.

Finally, Van Heuvelen *et al.* describe how a series of modules, each combining chemistry content and societal impact, were combined to reinvigorate a general chemistry sequence at Harvey Mudd College.³⁶ Examples of societal impacts related to SDGs include the Haber–Bosch process in the context of synthetic fertilizers, chemical weapons, water purification systems, ozone (both smog formation and stratospheric ozone depletion), metal-free catalysts, affordable and clean energy, and powering the car of the future. In some ways, the work described by Van Heuvelen *et al.* brings together the two approaches described in this chapter of overall course redesign (*e.g.*, SENCER) and more focused learning activities (*e.g.*, a module or case study).

Many of the case studies and modules described to this point do not, in their original presentation, contain explicit connections to sustainability and the SDGs. But these connections would be straightforward for an instructor to make. The module developed by Ryno and Cottine on pesticides has a strong connection to sustainability, as well as to SDGs 2 (Zero Hunger), 3 (Good Health and Well-being), 6 (Clean Water and Sanitation), 14 (Life Below Water), and 15 (Life on Land). A chemistry instructor using this module could have students explore the ethics of using pesticides and fertilizers to feed the world's population. The module on the Flint water crisis would lend itself to making connections with SDGs 6 (Clean Water and Sanitation) and 10 (Reduced Inequalities).

The ACS Green Chemistry Institute has been coordinating the development of a series of modules whose topics are taken from the standard curricula for general and organic chemistry.³⁷ Sustainability, UN SDGs relevant to the module topic, and green chemistry concepts are incorporated

throughout each module. The topics of these modules include Stereochemistry: Introduction to Chirality (linked to compounds designated as essential medicines), Ideal Gases and the Nitrogen Cycle, Thermochemistry and Energy Use, and Refrigerants and Lewis Structures. As of August 2025, 13 modules are available, with more to be released in the near future.

8.2.3 Resources for Connecting Chemistry to Ethics

8.2.3.1 Books

Mentioned earlier in the chapter, the books by Kovac and Mehlich include many cases for student discussion. In his book, *The Ethical Chemist*, Kovac includes 79 short cases (each less than a page in length); however, few of these deal with situations focused on “outward facing” professional ethics.¹⁶ Mehlich’s book, *Good Chemistry: Methodological, Ethical, and Social Dimensions*, contains several cases for discussion at the beginning of each chapter.¹⁰ With five chapters in the section titled “Chemistry and Society”, this results in significantly more cases in this book related to the impact of chemistry on society.

Another book to consider is *Ethics of Chemistry: From Poison Gas to Climate Engineering*.³⁸ This volume, edited by Schummer and Borsen, is a compilation of 19 articles originally published in “Hyle: International Journal for Philosophy of Chemistry”. The chapter authors, evenly divided between the US and European countries, provide a more international perspective. Although unlikely to serve as a textbook in an undergraduate course, this book nonetheless is a useful resource for instructors wishing to learn more before starting to design activities for students.

8.2.3.2 Websites

Immensely valuable to engaging students with real-world issues within chemistry courses is the website *Our World in Data*.³⁹ Max Roser, an economist at the University of Oxford, began the project in 2011, and *Our World in Data* has evolved to the point where it is now produced as a collaborative effort between researchers at the University of Oxford and the non-profit organization Global Change Data Lab. As of 2025, the site provides over 14 000 interactive charts, and individual entries are gathered into ten topics. All material on the site is freely available to the public under a Creative Commons license.

For example, consider the Energy and Environment topic. It contains 23 subtopics (Box 8.1), including access to energy, renewable energy, various forms of pollution, clean water and sanitation, fossil fuels, greenhouse gas emissions, and climate change. Within each topic are visualizations as well as summaries of key points. Some visualizations present the data over time and allow users to focus on a particular year. Other visualizations provide the option for changing from a graph to a map or changing the axes on a particular graph. Images can be

Box 8.1 Topics available (partial list) in the Energy and Environment section of *Our World in Data*.³⁹

Climate change	CO ₂ and greenhouse gas emissions	Air pollution
Outdoor air pollution	Indoor air pollution	Ozone layer
Energy	Access to energy	Fossil fuels
Renewable energy	Nuclear energy	Metals and minerals
Natural disasters	Biodiversity	Fish and overfishing
Land use	Water use and stress	Wildfires
Animal welfare	Forests and deforestation	Plastic pollution

downloaded as PNG (Portable Network Graphic) files for use in presentations or other documents. Data from a particular visualization can be downloaded as a CSV (comma separated values) file that can be opened in excel. Data sources, *e.g.*, United Nations agencies, the World Bank, the World Health Organization, and academic sites, are clearly identified.

8.3 Teaching and Learning a Chemistry Topic with an Explicit Ethical Dimension

This section presents two examples of how ethical dimensions can be incorporated into chemistry topics that utilize some of the resources described in earlier sections of this chapter. The first example, refrigerants (a context for learning how to draw Lewis structures and identify shapes of molecules), works well in entry-level courses. The second example, the chemical mechanisms of enzymes important in the lifecycle of the HIV virus that causes AIDS, illustrates how this approach can be used in an upper-level course such as biochemistry.

8.3.1 Student Learning Outcomes

Explicitly connecting chemical concepts to issues of sustainability or the UN SDGs does not change the student learning outcomes for chemical concepts. Rather, what changes is that the instructor is also concerned with helping students develop habits of mind related to integrative learning, *i.e.*, making connections between chemistry and the ethical dimensions related to sustainability. Box 8.2 provides two general learning outcomes that can be useful in any course that connects chemistry topics with professional ethics.

More specific objectives may be appropriate for courses like physical chemistry, inorganic chemistry, or biochemistry, but these will vary. The learning outcomes in Box 8.2 are about developing habits of mind and consequently will require multiple opportunities over time (either in the same course or across courses) for students to develop. The two sections that follow offer readers a better sense of how they might bring together

Box 8.2 Student learning outcomes for ethical questions and issues in chemistry courses.

1. Choose an application of chemistry to sustainability and describe some of the ethical questions/concerns relevant to that application.
2. Evaluate ethical aspects and implications of an application of chemistry to sustainability and provide reasons for a particular choice.

chemistry, sustainability, and ethical dimensions in both a foundational course (general chemistry) and an upper-level course (biochemistry).

8.3.2 General Chemistry – Refrigerants, Lewis Structures, and Shapes of Molecules

8.3.2.1 *The Cold Chain and Sustainability*

Refrigeration has been called one of the great engineering achievements of the 20th century.⁴⁰ It has helped reduce spoilage of food, is required for the stability of vaccines and other medical supplies, and has reduced the health impacts of extreme heat in multiple regions of the globe. Anthropogenic global warming linked to human activity has made it even more imperative that a functional and sustainable temperature-controlled supply chain (often referred to as a “cold chain”) be available to people around the globe, as the need for refrigeration and cooling technology will increase significantly. While new technologies for cooling are likely to be developed in the near future, refrigeration will still remain an important way to control and maintain desired temperatures.

Vapor-compression refrigeration is the technology most familiar to people.⁴¹ In this process, a chemical substance (refrigerant) absorbs heat under low pressure and passes from the liquid to the vapor phase. The refrigerant is then compressed under pressure back to the liquid phase, releasing heat into the surroundings. The nature of this cyclic process requires that refrigerants be volatile fluids, typically small molecules with boiling points in the range of $-50\text{ }^{\circ}\text{C}$ to $+30\text{ }^{\circ}\text{C}$.

A refrigerant has numerous desirable/required characteristics: chemical stability, low toxicity, minimal or no flammability, maximum energy efficiency, minimal environmental impact in terms of both global warming potential and ozone depletion potential, thermodynamic properties that match the system and application requirements, long operational life, and compatibility with other materials used in refrigeration equipment.⁴¹ As McLinden *et al.* state, “There exists, however, no single ideal refrigerant. The desired properties of the refrigerant depend on the type of equipment and the operating conditions (primarily heat sink and source temperatures)”.⁴¹ Finding ways to expand access to refrigeration and cold chain storage that

are more efficient and less damaging to the environment is an area of active research and development.⁴²

8.3.2.2 *Refrigerants and Teaching Lewis Structures and Shapes of Molecules*

Lewis structures and molecular shapes are important topics in first-year chemistry. A quick examination of the list of pure-fluid refrigerants provided as supplemental information to McLinden and Huber's review⁴¹ shows dozens of compounds that are suitable for teaching students how to draw valid Lewis structures. Appropriate choices include CFCs (chlorofluorocarbon compounds), HCFCs (hydrochlorofluorocarbon compounds), HFCs (hydrofluorocarbon compounds), and HFOs (hydrofluoroolefin compounds). These compounds vary significantly in their flammability, toxicity, and environmental impact.

A chemistry instructor interested in using refrigerants as the context for learning Lewis structures can start by taking a few minutes to introduce the current and future importance of refrigeration.⁴³ This can be followed by guiding students through the process of drawing Lewis structures for various refrigerant compounds. McLinden and Huber⁴¹ identify three different phases in the search for new refrigerants, and their approach can be used as a guide to organize refrigerants into different groups. Refrigerants in the first group include NH_3 , SO_2 , and C_3H_8 (propane). After drawing Lewis structures for these compounds, an instructor can use information from PubChem,^{44,45} a large free database with information on many substances, to examine their toxicity (Box 8.3). By pointing out the toxicity and flammability concerns with the first generation of refrigerants, the instructor can help students understand the motivation for developing new refrigerants that are nontoxic and non-flammable.

Second generation refrigerants are CFCs, the chlorofluorocarbon compounds. Unlike first generation refrigerants, CFCs are nontoxic and non-

Box 8.3 Information (partial list) for substances found in PubChem.⁴⁴

- Structures
- Names and Identifiers
- Chemical & Physical Properties
- Pharmacology & Biochemistry
- Use & Manufacturing
- Safety & Hazards
- Toxicity
- Associated Disorders and Diseases
- Literature
- Patents

flammable. These compounds can provide students with more practice in drawing Lewis structures. At the same time, the instructor can introduce how CFCs catalyze stratospheric ozone depletion and why that is problematic. The 1987 Montreal Protocol on Substances that Deplete the Ozone Layer⁴⁶ can be highlighted as an example of a successful international partnership related to sustainability.

In response to the environmental problems created by CFCs, third generation refrigerants such as HCFCs and HFCs were developed. Like CFCs, these compounds are also nontoxic and non-flammable but have little or no ability to deplete stratospheric ozone. However, they also function as greenhouse gases, and so chemists have developed a new generation of refrigerants, such as R-1234yf ($C_3H_2F_4$). Instructors can use specific examples of HCFCs and HFCs as well as compounds like R-1234yf for students to practice drawing Lewis structures. Possible out-of-class activities to complement the in-class work are shown in Box 8.4.

Finally, the compounds used to help students learn to draw Lewis structures can serve as examples for learning other topics typically found in first-year chemistry. For example, predicting the shapes of molecules is often taught immediately after Lewis structures, and many of the refrigerant compounds also work well for learning Valence Shell Electron Pair Repulsion (VSEPR) rules for predicting geometry and shape around a central atom. The same compounds can also be used for identifying the hybridization of a particular atom. Using refrigerant compounds as illustrative examples and practice when teaching several different chemistry topics can provide additional opportunities to engage students with the process of thinking how to balance characteristics such as safety, toxicity, and environmental impact.

Box 8.4 Out-of-class activities relating to refrigeration.

#1 Choose three refrigerants, draw their Lewis structures, examine their atmospheric lifetimes, and report safety and hazard information using information from PubChem.

#2 Read the article, “Africa’s Cold Rush and the Promise of Refrigeration” (Nicola Twilley, *The New Yorker*, August 15, 2022). What are some of the challenges described in the article to providing sustainable cooling and cold chains to regions in Africa? What role might chemistry play in meeting those challenges?

#3 What is the connection between refrigeration and greenhouse gas emissions? Visit this website on the Global Cooling Pledge, <https://coolcoalition.org/>.

Depending on class size and instructor preference, the out-of-class work on selected refrigerants or the Twilley article can also serve as the starting point for group discussions during class.

8.3.3 Biochemistry – HIV/AIDS, HIV Protease, and Enzyme Catalysis

SDG 3 states “Ensure healthy lives and promote well-being for all at all ages”. The 13 targets within the goal focus on a wide range of health issues, including HIV/AIDS, tuberculosis, malaria, maternal and infant deaths, noncommunicable diseases, addiction, environmental health issues, and development/availability of vaccines and drugs.²⁹ More specifically, Target 3.3 is to end the epidemics of AIDS, tuberculosis, malaria, and other communicable diseases.

The first AIDS cases were reported in the early 1980s. By 2024, the Joint United Nations Programme on HIV/AIDS (UNAIDS) reported an estimated 88.4 million people had been infected with the HIV virus and 42.3 million people had died from AIDS-related illnesses since the start of the epidemic.⁴⁷ In 2023, 39.9 million people globally were estimated to be living with HIV, with only 77% having access to antiretroviral therapy. Approximately 630 000 people died in 2023 from AIDS-related illnesses. While the number of people with access to antiretroviral therapy and the number of AIDS-related deaths in 2023 reflect real progress compared to the early years of the 21st century, the global community is falling significantly short of ending the epidemic. As Alan Whitesides wrote in *HIV/AIDS: A Very Short Introduction*, “Preventing HIV transmission and successfully treating patients needed more than laboratory work. The epidemic is lodged in parts of the world where poverty and inequity are rampant. The gendered nature of transmission and its location among marginal populations is critical. Dealing with this disease means understanding the science, and then looking beyond it”.⁴⁸

Viral life cycles are at the heart of how HIV or SARS-CoV-2 infect cells. Completion of these life cycles absolutely depends on the proper functioning of many proteins that serve as enzymes catalyzing various steps in the life cycle, such as nucleic acid synthesis or cleavage of larger proteins into smaller functional forms. These enzymes are commonly the target of antiviral drugs, and knowledge of the structure and catalytic mechanism of key viral enzymes can make major contributions to the rational design of new antiviral drugs.

For decades, the function of enzymes as catalysts at a molecular level has been an important topic in undergraduate biochemistry courses. All enzymes share common principles for how they function as biological catalysts. They have evolved to have optimal favorable noncovalent interactions with the transition state(s) of the reaction catalyzed, lowering the activation energy barrier and accelerating the reaction rate by as much as a million-fold in some cases. In addition, enzymes can utilize several general catalytic strategies. These include bringing two substrates into close proximity and the correct orientation (which reduces the entropic barrier to the reaction), acid–base chemistry, and covalent catalysis that involves the temporary formation of covalent bonds with one or more reaction intermediates. Small molecules can inhibit the function of enzymes, either through competing with the normal substrates for binding to the enzyme active site or through binding to other sites on the enzyme and altering the protein’s conformation.

The classic example used to teach these concepts is the digestive enzyme chymotrypsin. But these concepts can also be illustrated using two key enzymes that are part of the lifecycle of the HIV virus, the causative agent of AIDS. The first, reverse transcriptase, is involved in the early stages of viral infection of a cell and catalyzes the synthesis of a double-stranded DNA molecule from the single-stranded RNA genome of the virus. The double-stranded DNA is key to the virus's ability to integrate into the host cell genome and go undetected for years. The second, HIV protease, catalyzes the cleavage of a larger protein into smaller functional proteins as part of the viral maturation process. Immature virus particles are unable to infect cells, and so blocking the maturation process through inhibition of HIV protease prevents new cells from being infected.

In addition, HIV protease is a good example of enzymes having optimal favorable noncovalent interactions with the transition state as well as illustrating the importance of acid–base chemistry and proximity/orientation. Protease inhibitors used in antiretroviral therapy also serve as a good example of using knowledge of an enzyme's catalytic mechanism to design a long-lasting inhibitor that mimics features of the transition state for the enzyme catalyzed reaction. For reverse transcriptase, non-nucleoside inhibitors block enzyme function by binding to a site on the protein distinct from the active site and altering the enzyme's conformation. They can be used as an example of allosteric inhibition of enzyme function, an important regulatory mechanism for enzyme activity.

Incorporating the mechanism of HIV protease into undergraduate biochemistry courses in place of the mechanism of chymotrypsin also creates opportunities to have students engage with other aspects of the AIDS pandemic. Articles from publications such as *The New Yorker*, op-ed/commentary essays from journals like *Science* or *Nature*, or selections from the wide range of literary works centered on HIV/AIDS (such as Stephanie Nolen's *28: Stories of AIDS in Africa*⁴⁹) can be provided to students as short complementary readings. Information on the incidence/prevalence of HIV infections in different regions of the world or age groups, changes in AIDS-related mortality, or changes in the number of HIV positive individuals receiving antiretroviral drugs can be easily incorporated using graphics freely available from *Our World in Data* or UNAIDS. Questions related to access to medications and intellectual property rights for biomedical research related to new treatments for HIV infection can be raised with students.

8.3.4 Assessment

For students to develop the habits of mind involved in describing and evaluating ethical aspects of applying chemistry to meet challenges related to sustainability and the SDGs, they must be provided with opportunities to do this. The instructor must do more than simply introduce these aspects in a course; rather, students have to do things that will require using these habits of mind. Two ways for chemistry instructors to provide these

opportunities are discussion and writing. Regardless of which approach an instructor chooses to use in a particular class, students can be asked to identify, describe, or evaluate ethical aspects of an application of chemistry. Student work can be based on examples the instructor has incorporated into the class or can draw from other materials (such as websites or articles) that students read outside of class.

8.3.4.1 Discussion

Barkley and Major summarize many of the benefits of effective class discussions, describing different ways to categorize discussions and the important characteristics of each category.⁵⁰ For the focus of this chapter, perhaps the two most important categories are:

- spontaneous *vs.* planned, and
- in-person *vs.* online.

Spontaneous discussions are unplanned and allowed to develop in a natural way. While they require less preparation on the part of the instructor, they do not necessarily result in the depth of exploration that a planned discussion can provide. However, effective planned discussions require a lot of preparation on the part of the instructor. Anyone interested in learning more about how to plan effective discussions should consult the chapter on facilitating discussions in Barkley and Major.⁵⁰

Online discussions provide a nice option for instructors who are concerned about having enough class time for effective discussions. Discussion forums and chat rooms are examples of the environments that can support online discussion. Online discussions offer additional flexibility in that they can be done either synchronously (everyone participating at the same time) or asynchronously (individual students participate at different times as their schedules allow).

8.3.4.2 Writing

Bean and Melzer summarize the research about the relationship between writing and critical thinking.⁵¹ The form of writing most relevant to the focus of this chapter is what Bean and Melzer call “informal exploratory writing”, *i.e.*, writing “to discover, develop, and clarify our own ideas”.⁵¹ Chemistry instructors not familiar with this approach to writing may have concerns about the time it might take to incorporate this into a course, the student response to these assignments, and/or the potential grading load. Bean and Melzer provide suggestions that address these concerns and make a strong argument for incorporating informal writing in courses in which instructors want students to connect chemistry applications and ethical considerations.

Forms of exploratory writing can include notebooks, reading logs, journals, or even letters to the editor. Written posts in a discussion forum can

also function as a form of informal writing. Templates to structure informal writing can be found in several publications.^{52–54} The books by Barkley and Major and by Angelo and Zakrajsek are compilations of 50 or more techniques that can be used to engage students, provide formative feedback, or assess accomplishment of learning outcomes. For each technique, the authors provide an overview, directions for using the technique, examples from specific courses, and suggestions for how faculty can evaluate student work for more insight.

The Contemporary Issues Journal is an example of a technique that would be well suited for use in chemistry courses in which instructors are incorporating sustainability and the SDGs. Students are asked to look for recent events or developments that connect to chemistry and sustainability, then create journal entries where they analyze what they found for connections to course concepts. The journals can be collected at various points during the course or at the end.

Another assessment technique is The Ethical Dilemma, where students are presented with a vignette that poses an ethical problem related to the application of chemistry to sustainability or to the SDGs. After reading the scenario, students write a brief response to the situations. Student responses can also serve as the starting point for in-class discussions.

Chemistry instructors interested in the possibility of using some different structures for informal writing may find Jessica Singer Early's *Next Generation Genres: Teaching Writing for Civic and Academic Engagement*⁵⁵ a helpful resource. Early focuses on different writing genres that offer new ways to engage students with how course concepts connect to the real world. Genres in her book that seem particularly well suited to exploring the ethical aspects of chemistry applications to sustainability include the public service announcement, infographic, and op-ed. Each of these genres is the focus of a separate chapter in which Early provides more detailed guidance on how to create assignments.

With the recent availability of generative AI programs like ChatGPT, chemistry instructors are exploring how these tools might be effectively and appropriately used in chemistry courses. In the context of connecting chemistry applications related to sustainability and the SDGs to ethical aspects, an approach described by Pence *et al.*⁵⁶ may be a useful starting point. The authors describe how ChatGPT was used as a component of several assignments in an upper-level inorganic chemistry course focused on critical thinking. One assignment had students select an article from the ACS weekly periodical, Chemical & Engineering News,⁵⁷ and then use ChatGPT to generate a summary. Students then responded to a series of questions (adapted from a critical thinking rubric) that required them to analyze what ChatGPT generated. In a second assignment, students were individually assigned primary research literature questions from a problem set and asked to evaluate how well the generative AI program could find answers to the same questions. While the work described by Pence *et al.* was not connected to sustainability

and the SDGs, their approach could easily be adapted for the examples described in this chapter.

8.4 Closing Thoughts

Bringing ethical and societal considerations into a chemistry course is not about finding a single solution or the best solution. As Mehlich has written, "...ethical reflection allows one to refract the variety of views, identify overlaps and differences, or systematize and categorize types of arguments and their underlying worldviews".¹⁰ Gardner and Shulman describe the concept of good work, which "...consists of three facets: excellence in practice of the profession; an enduring concern with the social and ethical implications of one's work; and a feeling on the part of the practitioner that he or she is engaged in work that matters and that feels good".¹¹

If the next generation of chemists are to have an "enduring concern with the social and ethical implications" of their work, this will only come about if our students today are challenged to think about those implications as part of their educational experience. Bringing ethical and societal considerations of how chemistry is applied to meet the challenges of achieving sustainability and meeting the SDGs has the potential to be a powerful way to engage students in this aspect of becoming a chemical professional.

References

1. World Commission on Environment and Development, *Our Common Future*, Oxford University Press, New York, 1987.
2. G. M. Whitesides and J. Deutch, *Nature*, 2011, **469**, 21.
3. G. M. Whitesides, *Angew. Chem.*, 2015, **54**, 3196.
4. S. Matlin, G. Mehta, H. Hopf and A. Krief, *Nature Chem.*, 2016, **8**, 393.
5. S. A. Matlin, A. Krief, H. Hopf and G. Mehta, *Angew. Chem., Int. Ed.*, 2021, **60**, 25610.
6. D. Cole-Hamilton, *Chem. – Eur. J.*, 2020, **26**, 1894.
7. National Academies of Sciences, Engineering, and Medicine, *The Importance of Chemical Research to the U.S. Economy*, The National Academies Press, Washington, DC, 2022, DOI: 10.17226/26568.
8. Responsible Conduct of Research Training, <https://oir.nih.gov/sourcebook/ethical-conduct/responsible-conduct-research-training> (accessed August 2025).
9. Responsible and Ethical Conduct of Research, <https://new.nsf.gov/policies/responsible-research-conduct> (accessed August 2025).
10. J. Mehlich, *Good Chemistry: Methodological, Ethical, and Social Dimensions*, Royal Society of Chemistry, Cambridge, 2021.
11. H. Gardner and L. S. Shulman, *Daedalus*, 2005, **134**, 13.
12. The Chemical Professional's Code of Conduct, <https://www.acs.org/careers/career-services/ethics/the-chemical-professionals-code-of-conduct.html> (accessed August 2025).

13. Royal Society of Chemistry Code of Conduct, <https://www.rsc.org/membership/membership-regulations> (accessed August 2025).
14. The Hague Ethical Guidelines, <https://www.opcw.org/hague-ethical-guidelines> (accessed August 2025).
15. Global Chemists' Code of Ethics, <https://www.acs.org/content/dam/acsorg/global/international/scifreedom/global-chemists-code-of-ethics-fi-2016.pdf> (accessed August 2025).
16. J. Kovac, *The Ethical Chemist: Professionalism and Ethics in Science*, Oxford University Press, New York, 2nd edn, 2018.
17. W. M. Sullivan, *Work and Integrity: The Crisis and Promise of Professionalism in America*, Jossey-Bass, San Francisco, 2nd edn, 2004.
18. A. Colby and W. M. Sullivan, *Univ. St. Thomas Law J.*, 2008, 5, 404.
19. G. Marino, *Ethics: The Essential Writings*, Modern Library, New York, 2010.
20. SENCER About Us, <https://sencer.net/about-us/> (accessed August 2025).
21. W. D. Burns, in *Science Education and Civic Engagement: The Next Level*, ed. R. D. Sheardy and W. D. Burns, American Chemical Society, Washington DC, 2012, ch. 1, pp. 1–16.
22. SENCER Model Courses, <https://sencer.net/model-courses/> (accessed August 2025).
23. Undergraduate Biochemistry Through Public Health Issues, <https://archive.ncsce.net/undergraduate-biochemistry-through-public-health-issues/> (accessed August 2025).
24. M. A. Fisher, in *Citizenship Across the Curriculum*, ed. M. B. Smith, R. S. Nowacek and J. L. Bernstein, Indiana University Press, Bloomington, 2010, ch. 6, pp. 110–131.
25. M. A. Fisher, in *Connected Science: Strategies for Integrative Learning in College*, ed. T. A. Ferrett, D. Geelan, W. M. Schlegel and J. L. Stewart, Indiana University Press, Bloomington, 2013, ch. 3, pp. 31–39.
26. M. A. Fisher, *J. Chem. Educ.*, 2019, 96, 2715.
27. R. Marks and I. Eilks, *Int. J. Environ. Sci. Ed.*, 2009, 4, 231.
28. M. L. Caspers and E. S. Roberts-Kirchhoff, *Biochem. Mol. Biol. Educ.*, 2003, 31, 298.
29. Ensure Healthy Lives and Promote Well-Being for All at All Ages, <https://sdgs.un.org/goals/goal3> (accessed August 2025).
30. C. P. McClure and A. L. Lucius, *J. Chem. Educ.*, 2010, 87, 1171.
31. S. Pullen and K. Brinkert, *J. Chem. Educ.*, 2014, 91, 1569.
32. L. Rowe, *J. Chem. Educ.*, 2020, 97, 1944.
33. R. Blonder, E. Zemler and S. Rosenfeld, *Chem. Educ. Res. Pract.*, 2016, 17, 1145.
34. L. M. Ryno and C. Cottine, *J. Chem. Educ.*, 2018, 95, 1771.
35. P. Buckley and E. Fahrenkrug, *J. Chem. Educ.*, 2020, 97, 1327.
36. K. M. Van Heuvelen, G. W. Daub, L. N. Hawkins, A. R. Johnson, H. Van Ryswyk and D. A. Vosburg, *J. Chem. Educ.*, 2020, 97, 925.
37. Green Chemistry Learning Modules, <https://www.acs.org/green-chemistry-sustainability/education/teaching-modules.html> (accessed August 2025).

38. *Ethics of Chemistry: From Poison Gas to Climate Engineering*, ed. J. Schummer and T. Børsen, World Scientific Publishing Company, Singapore, 2021.
39. Our World in Data, www.ourworldindata.org (accessed August 2025).
40. G. Constable and B. A. Somerville, *A Century of Innovation: Twenty Engineering Achievements that Transformed Our Lives*, John Henry Press, Washington, DC, 2003.
41. M. O. McLinden and M. L. Huber, *J. Chem. Eng. Data*, 2020, **65**, 4176.
42. Clean Cooling Collaborative, <https://www.cleancoolingcollaborative.org/> (accessed August 2025).
43. Centre for Sustainable Cooling, <https://www.sustainablecooling.org/> (accessed August 2025).
44. PubChem, <https://pubchem.ncbi.nlm.nih.gov/> (accessed August 2025).
45. S. Kim, *Curr. Protoc.*, 2021, **1**, e217.
46. Montreal Protocol, <https://ozone.unep.org/treaties/montreal-protocol> (accessed August 2025).
47. The Urgency of Now: AIDS at a Crossroads, <https://crossroads.unaids.org/> (accessed August 2025).
48. A. Whitesides, *HIV/AIDS: A Very Short Introduction*, Oxford University Press, New York, 2nd edn, 2017.
49. S. Nolen, *28: Stories of AIDS in Africa*, Walker & Co., New York, 2007.
50. E. F. Barkley and C. H. Major, *Engaged Teaching: A Handbook for College Faculty*, SocialGood, Richmond, CA, 2022.
51. J. C. Bean and D. Melzer, *Engaging Ideas: The Professor's Guide to Integrating Writing, Critical Thinking, and Active Learning in the Classroom*, Jossey-Bass, Hoboken, NJ, 3rd edn, 2021.
52. E. F. Barkley and C. H. Major, *Student Engagement Techniques: A Handbook for College Faculty*, John Wiley & Sons, Incorporated, Newark, 2nd edn, 2020.
53. E. F. Barkley and C. H. Major, *Learning Assessment Techniques: A Handbook for College Faculty*, Jossey-Bass, San Francisco, 2016.
54. T. A. Angelo and T. D. Zakrajsek, *Classroom Assessment Techniques: Formative Feedback Tools for College and University Teachers*, John Wiley & Sons, Inc., Hoboken, 3rd edn, 2024.
55. J. S. Early, *Next Generation Genres: Teaching Writing for Civic and Academic Engagement*, W. W. Norton & Company, New York, 2023.
56. H. E. Pence, G. Hightower, J. Forlenza, K. Leonard, A. McLellan, A. Suero, B. Amoah, M. Mbow, S. Borner, A. Castillo and L. E. Pence, *J. Chem. Educ.*, 2024, **101**, 3789.
57. C&EN, <https://cen.acs.org/> (accessed August 2025).

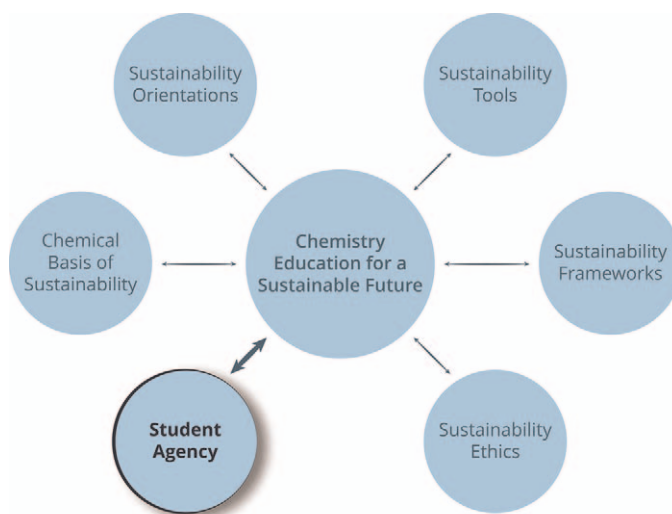
CHAPTER 9

Student Agency in Sustainability[†]

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9.1 Opening Thoughts

In 2015, all United Nations (UN) member states adopted the 2030 Agenda for Sustainable Development. The aim was to create a sustainable, equitable world that enhances the quality of life for everyone. It is based on 17 Sustainable Development Goals (SDGs) that provide countries with a framework for uniting in a common cause. These SDGs emphasize the need to combat poverty, improve health and education, reduce inequality, foster economic growth, and address climate change,¹ as described in Chapter 7.

Education stands as the cornerstone in the pursuit of sustainable development, responding to the need for an innovative educational paradigm — Education for Sustainable Development (ESD).² This distinctive approach is designed to equip students with the knowledge, skills, and values essential for grappling with the challenges of our era. Dedicated to instilling a profound comprehension of sustainability principles, ESD encompasses environmental stewardship, social equity, and economic viability. Through fundamental principles such as these, ESD aims to empower students to address the complexities of the modern world, thus fostering a generation capable of contributing to a more sustainable future.³ In shaping upcoming generations, ESD plays a crucial role by nurturing responsible citizens and future scientists.^{4,5}

How can chemistry instructors develop the agency of their learners to achieve the goals of the SDGs and ESD? This important question will be addressed in this chapter. Designing educational programs that develop student agency to promote a sustainable change in their environment is needed if change is to occur. The term *agency*, as the next section will explain, refers generally to the sense of control people have in taking actions. Ultimately, this chapter addresses how chemistry teachers and educators can act to support the development of student agency with respect to sustainability in their department, their institution, or more widely in their society.

9.2 Background

This section provides additional information about Education for Sustainable Development, including a discussion of the research findings. The findings point to the need for education that includes suggestions for behavioral change. Research also highlights the positive correlation between environmental knowledge and environmental behaviors. After providing a more detailed explanation of the term *agency*, the section concludes with a framework for student agency in sustainability, including a discussion of *agency-centered sustainability education*.

9.2.1 Education for Sustainable Development

Education for Sustainable Development provides students with the appropriate tools to make informed choices and participate in initiatives that

preserve the environment while also advancing economic prosperity and social equality for current and future generations.^{6,7} Additionally, ESD is essential for fostering collaboration and encouraging interdisciplinary approaches, which are fundamental prerequisites for effectively addressing the challenges of sustainability and their global nature.⁸

Mamlok-Naaman and Mandler conducted a study about education for sustainable development in high school through an inquiry-type chemistry laboratory program. One of their findings was that global climate change couples chemistry with fields such as economics, politics, domestic policy, and foreign affairs.⁹ In addition, the authors concluded that learning about the SDG for climate action and the other SDGs provides an excellent context for socio-scientific education. These conclusions are aligned with the environmental literacy report of the National Environmental Education and Training Foundation, which recommended that people should receive concrete suggestions on how to change their behavior.¹⁰

This environmental literacy report also noted a positive correlation between environmental knowledge and environmental behaviors. Therefore, one of the roles of chemistry education should be to help citizens react to sustainability and environmental issues by providing data and theories that define the problems, as well as the skills needed to address and cope with these problems. Chemistry teachers can support the development of chemical knowledge and critical thinking skills in their students. This knowledge and these skills can serve as lenses for interpreting the data, as suggested by Rap *et al.*¹¹

Sustainability education develops awareness and inspires proactive engagement in initiatives geared towards sustainable transformations. Within the perspective “Think globally, act locally”,¹² these transformations encompass societal changes with the overarching goal of safeguarding the well-being of both humans and the broader natural environment, while also promoting just and peaceful societies within the constraints of planetary boundaries.¹³ The societal changes are influenced by the culture of each society. We suggest that to enact these changes, teachers and students must become “agents of change”.

9.2.2 Agency

Agency encompasses an individual’s inherent capacity to engage in actions, make decisions, and assert his or her own intentions. The essence of *agency* is encapsulated in the subjective experience of having influence and mastery over one’s actions and the ensuing consequences.¹⁴

As a concept, *agency* connects to questions of world-wide importance. For example, the member countries of the Organisation for Economic Co-operation and Development (OECD) work together on challenges in our world today, including those relating to education. The OECD has tackled the same question that underlies the chapters in this book: *How can we better prepare students today for the challenges they will encounter tomorrow?* In response to

this question, the OECD published the “Learning Compass 2030”.¹⁵ This report is a dynamic learning framework that outlines a visionary path for the future of education. It offers guidance towards a desired future characterized by both individual and collective well-being. The concept of a Learning Compass is employed to underscore the importance of students mastering the ability to navigate autonomously through unfamiliar situations and environments.¹⁵

In the OECD report, *agency* is the fusion of purpose and responsibility. With this definition, *agency* can serve as both a goal for educational systems and a defining characteristic of effective learning. As a goal for educational systems, *agency* means a student exercising his or her sense of purpose and responsibility while learning to influence the people, events, and circumstances around him/her for the better. As a defining characteristic of effective learning, *agency* encourages students to actively set goals, to engage in reflective practices, and to responsibly and positively influence their environment.

Agency lies at the core of the OECD’s educational vision for 2030. This transformative concept embodies the proactive role of learners in shaping their educational journey. The OECD Future of Education and Skills 2030 initiative,¹⁵ which includes the Learning Compass, aims to cultivate a shared comprehension of the knowledge, skills, attitudes, and values essential for students in the 21st century. These learning and teaching frameworks are collaboratively developed by policymakers, researchers, school leaders, teachers, and students globally.³

The OECD envisions an educational landscape where students and educators work together, foster motivation, and define clear learning objectives and essential lifelong skills. Ultimately, this approach seeks to empower individuals not just with knowledge but also with the ability to navigate a dynamic world proactively and informedly.¹⁵

9.2.3 A Framework for Student Agency in Sustainability

By linking the principles of education for sustainability and student agency, we introduce a framework for student agency in sustainability.¹³ The framework is designed to serve as a guide for designing programs for sustainable education.

Guerra *et al.*¹⁶ proposed a conceptual framework for student agency for sustainability, based on Bandura.¹⁷ They claim that sustainability education encompasses instructional approaches that inspire proactive engagement in transformative initiatives for sustainability. Guerra *et al.*¹⁶ suggest a systematic integration of agency-centered sustainability education, which takes into account the psychological, social, and contextual factors in formal and informal learning settings. Their perspective on agency is based on the social cognitive tradition, where agency is regarded as a dynamic attribute that can materialize in diverse forms of actions due to interactions between various actors, environments, and cultural contexts.

Building on Guerra *et al.*,¹⁶ Koskela and Paloniemi developed a theoretical framework for *agency-centered sustainability education*,¹³ including six steps for designing agency-centered sustainability education in formal and informal learning settings. The six steps aim to strengthen learners' agency in sustainability education:

1. Deal with issues that the learners find valuable.
2. Enable learners to gradually develop competencies and strengthen their efficacy.
3. Include strategic contemplation of the most effective ways of acting.
4. Reflect on what has been done and how to deal with possible setbacks.
5. Frame sustainability in ways that maintain a vision of a desirable future.
6. Enable learners to experience the joy of doing meaningful things together.

In the next section, we present two different case studies that aim to promote awareness of the UN SDGs and advocate for proactive engagement. One case study is at the institutional level; the other is at the level of a chemistry class. In both case studies, the chemistry teacher plays a leading role in the design and implementation of the initiative. Utilizing the lens of an agency-centered educational framework, we aim to contribute insights about programs that address sustainable development goals and that support a culture of change.

9.3 Two Case Studies

9.3.1 Methodology

In each case study, we interviewed the chemistry educators who led the program at their institutions. Table 9.1 presents interview questions that were based on the six steps of agency-centered sustainability.¹³

The interviews were analyzed according to the framework of agency-centered sustainability education¹³ to identify how the six steps needed for agency-centered sustainability education are manifested in the two case studies.

In the sections that follow, we describe the case studies and their analysis; then we discuss the components that promoted students' agency and that can be adopted by chemistry educators. We highlight the role of the chemistry educator in promoting students' agency and discuss the challenges of the interdisciplinary nature of the SDGs and the continuation of the project.

9.3.2 Case Study #1: A Campus Sustainability Map

This case study is from the University of Wisconsin–Madison, USA, and is based on an interview with two of the individuals who created a campus sustainability map organized by the UN SDGs.¹⁸ The map highlights sustainability features at UW–Madison that contribute to campus and regional

Table 9.1 Interview questions.

Six design steps for agency-centered sustainability education	Interview question
The program should create diverse experiences that:	
(1) Deal with issues that the learners find valuable.	How did the program address student needs and interests and deal with issues that the learners found valuable and important?
(2) Enable learners to gradually develop competencies and strengthen their efficacy.	What kind of knowledge and competencies did the students develop while studying these activities? Did they develop self-efficacy to act? What is the evidence?
(3) Include strategic contemplation of the most effective ways of acting.	What were your considerations while choosing your way of acting and the specific participants involved?
(4) Reflect on what has been done and how to deal with possible setbacks.	What obstacles did you face while trying to advance your message? How did you cope with these obstacles while trying to advance your message?
(5) Frame sustainability in ways that maintain a vision of a desirable future.	Do you think that you managed to develop a program that will create hope with the learners? If so, how did you do it?
(6) Enable learners to experience the joy of doing meaningful things together.	Do you believe that the learners enjoyed your program? If so, how did you assess it? What did you do to support students' enjoyment?

sustainability. Users can select views of the map that correspond to the different SDGs (Figure 9.1). The map aims to (1) provide a user-friendly visual representation of campus sustainability, (2) share campus sustainability knowledge, (3) increase current sustainability efforts, and (4) highlight areas that could be improved.

The Campus Sustainability Map enables users to discover and explore campus sustainability components, for example, solar panels, certified Green Offices, and cultural centers. The map is geared towards a wide audience of students, staff, and faculty. The map is currently utilized in courses as a teaching tool and more widely as a campus orientation tool, both for those new to campus and for those seeking to learn more about campus sustainability. It provides real-world examples of environmental, economic, and social sustainability.

The map was launched in spring 2021, is updated regularly, and is featured on the UW–Madison Office of Sustainability website.¹⁹ As of spring 2024, it had received over 17 000 views. In addition, the map was shared through a wide variety of publicity channels, including through an article published in the monthly campus sustainability newsletter and later shared by campus departments and units.²⁰ The map was also shared on social media and at local, regional, and national conferences.

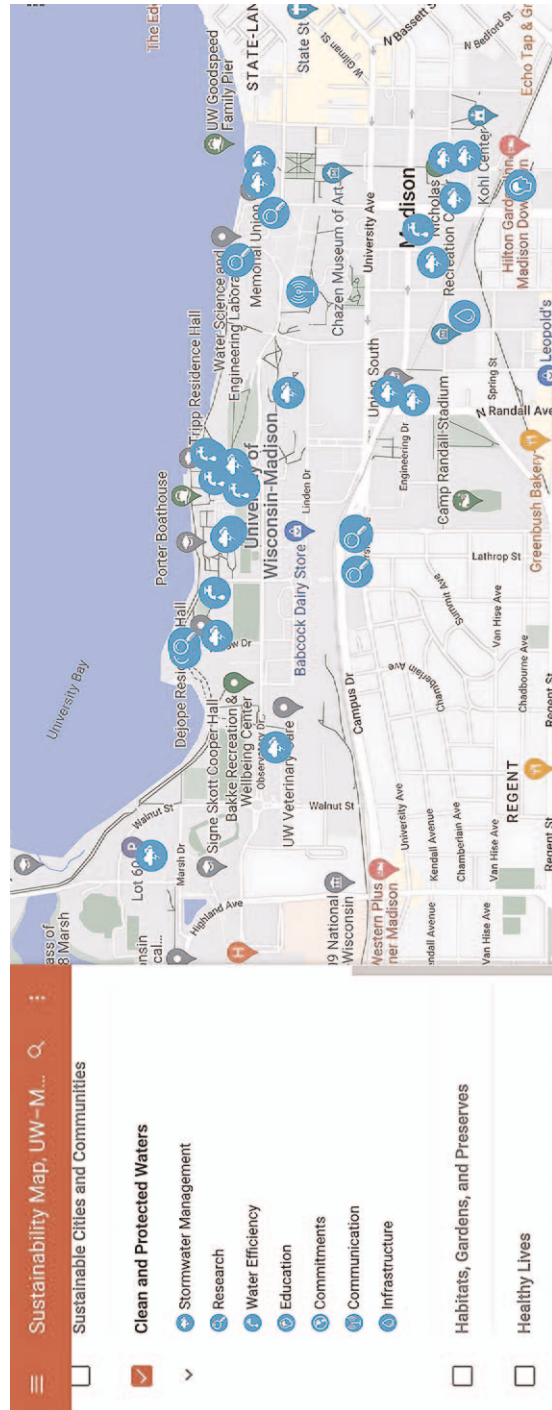


Figure 9.1 Screenshot of the University of Wisconsin-Madison Campus Sustainability Map.¹⁹ This view utilizes a set of blue icons to indicate campus initiatives that connect to UN SDG #14, Life Below Water. Reproduced from ref. 19 with permission from UW-Madison Office of Sustainability.

Audrey Stanton led the project, in conjunction with her colleagues at the UW–Madison Office of Sustainability including undergraduate student Mackenzie Thelen. This project formed the basis of Stanton’s master’s thesis, under Professor Cathy Middlecamp’s direction. Both Stanton and Middlecamp have taught undergraduate sustainability science courses at the university, including writing learning objectives and designing lab activities. In addition, both have held positions at the university-wide Office of Sustainability. Their ability to function in these roles has come from working with real-world campus examples.^{21,22}

The campus sustainability map uses the SDGs as an organizing principle:

“The SDGs provided a rationale by which to include or exclude campus features in our visual representation of campus sustainability. Furthermore, the SDGs have international standing and are well-vetted”.

– Audrey Stanton

When asked about their role as educators in promoting the SDGs, they commented:

“As university instructors, we see our role as multifaceted. Our activities included (but were not limited to) offering information that is clear, useful, thoughtful, and accessible, and finding ways to inspire and to motivate students to learn this information. Furthermore, we strive to make concepts relevant to students with varying perspectives. For example, if the environmental case for a sustainability choice does not interest a student, perhaps the social or economic case might. Additionally, we enjoy sharing examples of local, regional, national, and international sustainability policies and initiatives with students. This can be used to demonstrate how the SDGs can be scaled up or down”.

– Audrey Stanton, Cathy Middlecamp

The most challenging part of making a digital map is ensuring that it stays updated. To maintain the campus sustainability map, Stanton compiles an ongoing list of new campus initiatives and program updates. This list is cross-referenced with the SDGs to determine whether the potential features meet the criteria, and if so, how they should be organized on the map. The authors see the need for resources to keep maintaining the map:

“Without continuous updating, our map will slowly decline in its relevance. The issue of aging websites is by no means unique to our project, and the cultural shift we hope for is one in which resources will continue to be allocated to campus sustainability”.

– Audrey Stanton, Cathy Middlecamp

In 2024, the Chancellor of the University of Wisconsin-Madison launched an ambitious environmental sustainability initiative. This effort is designed to reduce the campus' environmental footprint, cultivate a culture of sustainability, build climate resilience, and foster innovation.²³

9.3.3 Case Study #2: “Speak to Me in Numbers”

This second case study is from the Weizmann Institute of Science, Israel and is based on an interview with a science teacher who was part of the development team of the program “Speak to Me in Numbers”.²⁴ This curriculum for ninth grade students, available in both Hebrew and Arabic, introduces students to some of the Sustainable Development Goals of the United Nations. Five units of this curriculum are currently available and are based on SDGs 3, 6, 7, 13, and 14, as shown in Figure 9.2.

The project was funded in 2020 by the Eddie and Jules Trump Family Foundation, “as part of the foundation’s focus on promoting excellence in middle school science and technology education”. In 2020, this program was launched with local middle school students who were enrolled in a high achievement science track. These students studied the program two additional hours per week throughout the year, in addition to their regular science studies in school.

In “Speak to Me in Numbers”, students analyze an issue related to one of the SDGs. By utilizing mathematical skills, they search for data-based solutions. After drawing conclusions based on the analysis of their data, the students suggest ways to actively influence their local environment. At the end of each unit, the students implement an activity that they designed. In this way, using data as well as their own calculations and data analysis, they act as change agents.

For example, consider this student-designed activity from SDG #13, Climate Action. The students proposed replacing all the school’s light bulbs with LED ones. Using data and calculations, they demonstrated the feasibility in terms of CO₂ emissions. But the students did not stop there; they also decided to examine the economic aspect, calculating how long it would take for the replacement cost to pay off. By taking action at the school level, they discovered through their calculations that the initiative was viable. The



Figure 9.2 Five of the 17 United Nations SDGs, currently part of the “Speak to Me in Numbers” program.²⁴ Reproduced from ref. 24 with permission from Weizmann Institute of Science.

school management replaced all the bulbs on the school campus. Then, the students approached the municipality, urging them to consider replacing the bulbs in all schools citywide. They wrote a well-reasoned, data-driven letter to advocate for this change in their city.

As another example, a group of students calculated the CO₂ emissions produced during the manufacture of disposable cups to quantify the reduction in CO₂ emissions when they stopped using these cups. Figure 9.3 shows students working at computers to analyze their data during the project. Other students convinced younger students at their school to ride their bikes to school, in order to reduce CO₂ emissions.

The science teacher interviewed for this case study, Ayshi Sindiani-Bsoul, has nine years of teaching experience. She joined the development team of the program “Speak to Me in Numbers”, on which she is conducting her doctoral research in the Department of Science Teaching, under the mentorship of Drs. Blonder and Rap. In her current research, she attempts to evaluate the implementation of the program in schools in Israel, shifting the discussion of sustainability challenges from emotional aspects towards real data analysis. She noted that through data it is easier to convince others and implement changes in a wider social and community environment.

Sindiani-Bsoul feels a personal responsibility to participate in activities that promote raising awareness of the SDGs and making an impact. She is convinced that this is the basis for convincing others to make changes in their environment. She mentioned the importance of the SDGs’ values of equality and supporting others. In addition, she has contributed to environmental efforts within her household, and believes that everyone can strive for some kind of change. She believes that this change depends only on the goodwill and understanding of the individual students.



Figure 9.3 As part of the “Speak to Me in Numbers” program, students work at computers to analyze data.

Sindiani-Bsoul said that during the science and chemistry classes she exposes the students to environmental problems, as well as to content knowledge. She claims that *“this will lead them to increase their motivation to make some kind of change”*. She also added that

“Thinking is very significant in our program, in order to influence students’ agenda. . . if they change their way of thinking they have the ability to define a goal, then act upon that goal to implement it”.

Sindiani-Bsoul’s main goal is that the students will implement it in their environment, and then transfer it to future generations. She said that indeed, there is evidence of the program’s impact beyond her students. One of the participants told her that she would teach her sister and brothers to achieve an understanding that would lead to sustainability, *e.g.*, to recycle their waste or turn off the lights in their home. In addition, Sindiani-Bsoul observed that in the schools there were many collaborations, *e.g.*, the computer personnel and the computer teacher discussed the issue of replacing the computers with mobile or stationary ones. The language teacher also participated by delivering a lesson centered on sustainability. Each teacher contributed differently. Furthermore, parents experienced a tangible impact and demonstrated an awareness of effective strategies to support their children’s educational journey.

In addition to spearheading the initiative within her own school, Sindiani-Bsoul assumes a leadership role in a professional development program. This program extends beyond her school and involves guiding teachers from other schools and providing support as they implement the curriculum.

When interviewed, Sindiani-Bsoul expressed surprise that not all students were aware of climate change issues, despite the Ministry of Education including it in the curriculum. However, her school did not cover climate change or the SDGs. Concerned about this gap, Sindiani-Bsoul introduced the “Speak to Me in Numbers” program to her outstanding 9th graders. She said the program encourages students to integrate math and science and think differently to promote change in their learning. It fosters self-directed learning and out-of-the-box thinking, helping students become independent learners. They explored new information to address environmental issues, such as interpreting graphs differently from typical science lessons. Sindiani-Bsoul acknowledged that not every student can easily combine math and science but encouraged them to tackle challenges independently. Sindiani-Bsoul mentioned the technical problems that she faced:

“There are always technical obstacles at my school, and at other schools as well. Therefore, I do not teach every lesson in the computer room. We have in each classroom a projector and a computer, and together with my cellular phone, it makes it a little easier for me to solve these obstacles. We screen the questions and discuss the issues, explain the problems, and the students continue the work at home”.

Sindiani-Bsoul expressed disappointment with the teachers who do not teach the program due to the curriculum load. She believes in the project's merits, and teaches it especially to the exceptionally talented students, who will later transfer its principles to other students. As a teacher, she plans to continue leading the program every year with new students. In addition, she plans to keep in touch with students from the previous course, who now study in high school.

Here is how Sindiani-Bsoul describes the enthusiasm of her students:

“The students had a lot of fun, and it is not just because they were doing something different, but also because they became independent learners. They studied, read, and analyzed on their own. I gave them only the basic background, and they did all the rest by themselves – they looked for information, discussed questions with each other, and drew conclusions. Based on their learning, the students considered several activism projects and after a class discussion, they chose the best ones to focus on. They designed an activity and conducted it. . . I saw how enthusiastic they were”.

From Sindiani-Bsoul's point of view, for the educational activity to continue, there is a need for a professional person, who really *“has their hand on the pulse of the schools”*. This person should visit schools, check the curriculum taught by teachers, and be aware of their challenges.

9.3.4 Discussion

The two programs presented in the previous section reflect the six design principles of agency-centered sustainability education that can support the development of students' agency for sustainability.¹³ The “Campus Map” is a campus-level project that can be executed in a school, college, or university; in contrast, the second project, “Speak to Me in Numbers”, is at the middle school classroom level. These two case studies demonstrate that chemistry teachers and educators play an important role in developing student agency. Understanding this role in promoting the six steps of developing students' agency-centered sustainability education (Section 9.2.3) could guide future chemistry teachers who aspire to develop student agency.

Design Step #1: Deal with issues that the learners find valuable. The first step aims to adapt the program to the unique environmental issues that the learners find valuable. The “Campus Map” was created in the context of the campus environment and is therefore relevant to the university as a whole. Adopting this approach, a chemistry teacher can map the school environment with her/his students to create the school's SDGs map. After promoting awareness of the SDGs, the chemistry teacher can then lead a discussion on how to address the unique needs of the school. For example, in the first case study, the instructors who created the “Campus Map” integrated it in their chemistry course. By connecting the map to an academic course, the instructors emphasized the importance of chemistry knowledge in

sustainability issues and provided a systematic academic approach to knowledge development.

Design Step #2: Enable learners to gradually develop competencies and strengthen their efficacy. In the “Speak to Me in Numbers” program, students plan their own activities after they learn and gather data about a specific SDG. Giving students an opportunity based on their knowledge and interest engages them and develops their agency. The role of the teacher is to allow students to choose the subject for their activism and to guide them to apply their scientific knowledge and skills while they access new information and data. In this way, the teacher supports the learners as they gradually develop their competencies and knowledge of issues and strengthen their sense of efficacy.

Design Step #3: Include strategic contemplation of the most effective ways of acting. In the “Speak to Me in Numbers” program, the teacher guided her students to consider different activities and to choose the one they would like to lead, based on their data analysis. Sindiani-Bsoul mentioned that her students developed several activities that would have the most impact on different communities. They chose to communicate the activities to the other students in school, teachers, and parents.

Design Step #4: Reflect on what has been done and how to deal with possible setbacks. When students are engaged in their activism, they tend to not stop to think about what they have done, what they have learned, and what should be done differently. The chemistry teacher can guide them through the process to support this reflective habit of mind that supports student agency. For example, the instructor who helped to create the campus sustainability map recognized that a possible setback would be the lack of resources to keep the map current and relevant. Accordingly, she guided the students to reflect on this and to figure out how to deal with it.

Design Step #5: Frame sustainability in ways that maintain a vision of a desirable future. It is desirable for students to have a realistic view about the general state of the environment while developing their agency, starting in their immediate environment. In this way, their agency will be a vehicle for offsetting their ecological anxiety by propagating hope, understood as “the belief in the possibility of a better future”.²⁶ Note that environmental hope is linked to agency thinking.²⁷ Rap *et al.* showed that the curriculum as well as the teacher in the “Speak to Me in Numbers” program have contributed to the development of environmental hope.²⁵ Environmental hope is also reflected in the “Campus Map” project as students and university staff send suggestions for what should be added to the map. This reflects their belief that the map can promote environmental change as well as indicates that they developed their activism.

Design Step #6: Enable learners to experience the joy of doing meaningful things together. The last step for agency-centered sustainability education emphasizes the joy of doing meaningful things together. Using the “Campus Map”, the students who explored social sustainability frequently noted that they were excited to know that this resource exists and remarked on what

they learned about campus. Similar sentiments were shared by those who utilized the map during campus orientation. In “Speak to Me in Numbers”, the teacher provided the opportunity to study differently, enabling self-learning that is interest-driven and supports the joy of the students during the learning process.

Thus, in these two case studies, we were able to identify the components that promoted students’ agency according to agency-centered sustainability education. The pivotal role of education, with a central focus on promoting personal sense of agency, agentic behavior, and interaction with the environment, is crucial for the attainment of the SDG global objectives. Teachers play a crucial role in embarking on these educational programs, initiating agency among their students to achieve sustainable goals.

9.4 Closing Thoughts

Education for Sustainable Development in chemistry curricula requires re-shaping science education goals towards a vision of environmental literacy.²⁸ It necessitates multiple approaches that integrate social, economic, and environmental aspects of science and technology.^{6,7}

Socio-scientific issues that are dealt with in the framework of ESD can neither be taught nor learned solely in a chemistry lesson. Aspects of a wide variety of other subjects, including physics, biology, and earth sciences, should be integrated in these lessons. For example, discussing the topic of climate change in the “Speak to Me in Numbers” program requires knowledge in chemistry, mathematics, technology, economics, and the environment. Its implementation requires interdisciplinary connections that are often absent in exclusively science-based curricula,²⁹ and these interdisciplinary connections will demand much of teachers.³⁰ They will need to learn the knowledge, skills, attitudes, and teaching strategies to teach these interdisciplinary topics.³¹

This chapter presents teachers as “agents of change” who can carry out the reform needed in the chemistry classroom. The beliefs of teachers must not be ignored.³² Therefore, we suggest that teachers who implement a new curriculum, especially an interdisciplinary program, should receive sustained support in order to gain interdisciplinary knowledge as well as assessment skills.

We may conclude that successful implementation of ESD programs may significantly enhance student agency across three interconnected dimensions:

1. *Personal sense of agency*: ESD programs can improve students’ subjective beliefs about their ability to initiate and control their behaviors in learning settings related to sustainability.
2. *Agentic behavior*: These programs provide opportunities for students to actively exercise agency through participation in real-world sustainability projects and initiatives.

3. *Interaction with the environment*: ESD approaches, especially those involving hands-on experiences like exploring campus sustainability features or executing an initiative that fosters activism, allow students to directly interact with their environment in meaningful ways.

By fostering these dimensions of agency, ESD programs empower students to become active participants in sustainability efforts, rather than passive recipients of information. This approach not only enhances their learning but also prepares them to be engaged, informed citizens capable of contributing to sustainable development in their future personal and professional lives. It is therefore highly important to engage dedicated individuals in ongoing efforts to maintain and update the initiatives that go beyond the design stage.

References

1. United Nations, <https://sdgs.un.org/2030agenda> (accessed August 2025).
2. United Nations Educational, Scientific and Cultural Organization, <https://unesdoc.unesco.org/ark:/48223/pf0000247444> (accessed August 2025).
3. S. I. Perwitasari, E. Hariyono and E. Susantini, *Int. J. Recent Educ. Res.*, 2023, **4**, 399.
4. A.-K. Holfelder, *Sustainability Sci.*, 2019, **14**, 943.
5. S. Taimur and H. Sattar, in *Quality Education, Encyclopedia of the UN Sustainable Development Goals*, eds. W. Leal Filho, A. M. Azul, L. Brandli, P. Gökçin Özüyar and T. Wall, Springer Nature, Switzerland AG, 2020, pp. 238–248.
6. R. Blonder and S. Rosenfeld, *J. Chem. Educ.*, 2019, **96**, 2700.
7. T. Ferguson, C. Roofe, L. D. Cook, S. Bramwell-Lalor and C. Hordatt Gentles, *Brock Educ. J.*, 2022, **31**, 63.
8. R. Laurie, Y. Nonoyama-Tarumi, R. McKeown and C. Hopkins, *J. Educ. Sustainable Dev.*, 2016, **10**, 226.
9. R. Mamlok-Naaman and D. Mandler, in *Chemistry Education for a Sustainable Society Volume 1: High School, Outreach, & Global Perspectives*, American Chemical Society, 2020, vol. 1344, pp. 69–78.
10. K. Coyle, *Environmental Literacy in America: What Ten Years of NEETF/Roper Research and Related Studies Say about Environmental Literacy in the U.S.*, Washington, D.C., 2005, <https://digitallibrary.un.org/record/3898826?v=pdf> (accessed August 2025).
11. S. Rap, S. Geller, D. Katchevich, H. Gbarin and R. Blonder, *Chem. Teach. Int.*, 2023, **5**, 143.
12. É. Darier and R. Schüle, *Local Environ.*, 1999, **4**, 317.
13. I.-M. Koskela and R. Paloniemi, *Environ. Educ. Res.*, 2023, **29**, 164.
14. J. W. Moore, *Front. Psychol.*, 2016, **7**, 1272.

15. Organisation for Economic Cooperation and Development, https://www.oecd.org/content/dam/oecd/en/about/projects/edu/education-2040/concept-notes/OECD_Learning_Compass_2030_concept_note.pdf (accessed August 2025).
16. A. Guerra, D. Jiang and X. Du, *Sustainability*, 2022, **14**, 1.
17. A. Bandura, *Perspect. Psychol. Sci.*, 2006, **1**, 164.
18. A. P. Stanton, M. J. Thelen and C. H. Middlecamp, *Sustainability Clim. Change*, 2021, **14**, 202.
19. Office of Sustainability University of Wisconsin–Madison, <https://sustainability.wisc.edu/campus-sustainability-map/> (accessed August 2025).
20. Office of Sustainability University of Wisconsin–Madison, <https://sustainability.wisc.edu/new-uw-madison-campus-sustainability-map-goes-live/> (accessed August 2025).
21. M. J. Kraak, R. E. Roth, B. Ricker, A. Kagawa and G. Le Sourd, *Mapping for a sustainable world*, United Nations, International Cartographic Association, United States of America, 2021, Mapping for a sustainable world/(un.org) (accessed August 2025).
22. R. B. Swain, in *Handbook of Sustainability Science and Research*, ed. W. Leal Filho, Springer International Publishing, Cham, 2018, pp. 341–355.
23. University of Wisconsin-Madison News, <https://news.wisc.edu/uw-madison-launches-ambitious-environmental-sustainability-initiative/> (accessed August 2025).
24. Speak to Me in Numbers, https://stwww1.weizmann.ac.il/numbers-talk/?page_id=897&lang=en (accessed August 2025).
25. S. Rap, R. Blonder, A. Sindiani-Bsoul and S. Rosenfeld, *Front. Educ.*, 2022, **7**, 871102.
26. E. Kelsey, *Can. J. Environ. Educ.*, 2016, **21**, 23.
27. D. Kerret, H. Orkibi, S. Bukchin and T. Ronen, *J. Environ. Educ.*, 2020, **51**, 434.
28. J. Sjöström, N. Frerichs, V. G. Zuin and I. Eilks, *Stud. Sci. Educ.*, 2017, **53**, 165.
29. R. Mamlok-Naaman, R. Ben-Zvi, A. Hofstein, J. Menis and S. Erduran, *Int. J. Sci. Math. Educ.*, 2005, **3**, 485.
30. J. Penick and R. Meinhard-Pellens (eds.), *Science/Technology/Society*, National Science Teachers Association, Washington, DC, 1984.
31. R. W. Bybee and S. Loucks-Horsley, in *Supporting change through professional development*, ed. B. Resh, BSCS Science Learning, 2000, pp. 41–48.
32. R. W. Bybee, *Reforming science education*, Teachers College Press, New York, NY, 1993.

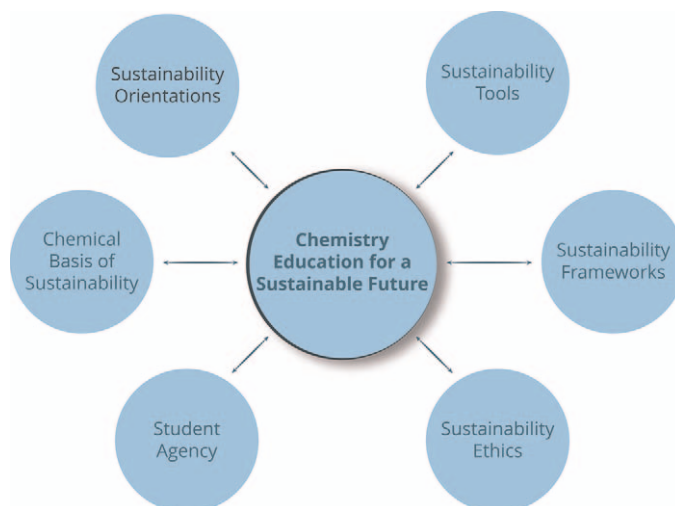
CHAPTER 10

Imagining Chemistry Education in 2050[†]

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10.1 Envisioning the Future: Learning and Teaching in 25 Years

As chemistry educators, we must recognize the complexity of future challenges so that we can adequately prepare the next generation to deal with them. A paradigm shift is necessary to move away from the assumption that Earth's resources are infinite and capable of absorbing our waste without consequences. To make this shift, educators must consider the needs of students, local communities, and all forms of life on Earth. Additionally, we can grow in our awareness and place focus on future innovation to drive the evolution of chemistry education toward sustainability.

The future is uncertain and ever-changing, but one constant is the process of learning. While we have a good understanding of how learning occurs, we must consider what students need to learn to build chemistry knowledge that will be valuable in their careers and prepare them for an interconnected and changing world. Critical reflection on our current teaching practices is necessary to explore strategies that can re-direct the future of chemistry education as the molecular basis of sustainability.¹ In addition, the emergence of new educational technologies has repeatedly influenced the trajectory of educational innovation. These technologies will shape the imagination necessary for envisioning the future of chemistry education 25 years from now.

10.1.1 Questions About Learning

Our desire to investigate new things drives our learning and development. The process of learning will always play a role in our future world. A key premise of this chapter is that to consider what students may be asked to learn in 25 years, one must first address what is known now about how people learn.

10.1.1.1 How Does Learning Occur?

A great deal about this topic has appeared over the past 25 years, including seminal work from the U.S. National Research Council in the book *How People Learn*.² In this book, the authors outline three key findings supported by research and influenced by teaching. First, students have preconceptions about how the world works and may fail to grasp new concepts if their prior understanding is not engaged. Second, for effective learning to occur, students need sound prior factual knowledge along with coherent and accurate ways to organize their ability to recall the facts and frameworks. Third, students must monitor and control their ways of thinking when engaging in learning, a cognitive skill called metacognition.

Flavell developed a framework that helps understand how metacognitive processes happen for learners and describes how actions related to metacognition help achieve learning goals. These actions include students using metacognitive strategies to judge their learning progress.³ A focus on how students learn can inform teaching practices that help them engage with

meaningful problem-solving activities and also help students develop the necessary skills to organize their factual knowledge. When related to sustainability challenges, these skills should help them understand why, when, and how knowledge and skills gained are relevant.²

10.1.1.2 *What Should be Learned?*

The relevance of topics to learners' interests meshes well with assertions that science generally, and chemistry in particular, will need to engage with issues of sustainability over the next 25 years. This book provides activities to engage students in meaningful learning about chemistry and its role in sustainability. These activities integrate orientations of chemistry such as green chemistry, sustainable chemistry, systems thinking, and circular chemistry; connecting chemistry to sustainability frameworks such as the UNSDGs and Planetary Boundaries frameworks; embedding ethical considerations in teaching and learning of chemistry; and using tools such as systems thinking and artificial intelligence (AI). As emphasized in Chapter 2, students require background knowledge of the accelerating changes being made to the planet due to the scale of human activities, the demand for energy, and the transformation of nutrients and biomass.

Two approaches to learning chemistry are possible: a zoomed-in approach, in which students examine chemicals and processes at various scales (atomic, molecular, particulate, and macroscopic), and a zoomed-out approach, in which they explore the interactions between chemical processes and broader systems (which include subsystems). As discussed in Chapter 4, these subsystems can explore mass/chemical input, energy requirements and reaction conditions, waste or by-products, intended uses, unintended impacts, planetary systems, and connections to socio-economic or industrial processes or impacts.

Together with developing foundational knowledge about the role of chemistry in socio-scientific issues, it is also critical for the next generation to deal with complex systems involved in sustainability challenges. Systems thinking (Chapter 4) is one skill that could help students understand and interpret complex systems through visualizing and examining the parts of a system, its interconnected relationships, its changing behavior over time, and emergent properties. Systems thinking capabilities also promote critical reasoning about scientific phenomena and professional skills, such as collaboration to deal with real-world issues and develop a desire to take action (Chapters 4 and 9).

In promoting the kinds of educational innovation that may shape the classrooms of 2050, the complexity of real-world contexts emerges as a challenge. For example, the contexts of air or water quality are likely to involve many parameters, some of which interact with each other. As a result, students may need to tap into new or different resources to propose a course of action. Although they might want to propose an easy fix, more likely than not, only a compromise will be possible. Realities such as these certainly will influence what our students learn, how they learn, and their understanding of the complex relationships in the natural world.

10.1.2 Questions About Teaching

Given the trajectory of understandings developed in cognitive science, future educators and researchers certainly will know much more about the process of learning. In turn, this enhanced knowledge will aid them in identifying how specific pedagogies can offer better prospects for student success. Even today, several of the core concepts of human learning can help guide instructors to envision the future of chemistry education. These include identifying student misconceptions, teaching in interdisciplinary contexts, creating opportunities for collaborative learning, leveraging artificial intelligence, and fostering student agency and stewardship. Each of these will now be examined in turn.

10.1.2.1 *Identifying Student Misconceptions*

It is well-established that students arrive in educational settings with pre-conceptions that they use to frame any new pedagogical experience in ways that may either help or hinder their learning. Student prior conceptions, often defined in terms of misconceptions, have been studied repeatedly in both chemistry education⁴⁻⁷ and environmental education.⁸ Identifying the state of misconceptions as content moves toward interdisciplinary topics⁹ may be an important component in determining what and how sustainability-related content will be taught in chemistry classrooms in 2050. When teaching green chemistry concepts, for example, students might have misconceptions about terms like “natural” or “renewable” and think that all-natural products are inherently safe due to their prior knowledge of eco-labels on consumer products. Thus, to avoid misconceptions, students need to be asked to elaborate on these terms to diagnose common misunderstandings.¹⁰

10.1.2.2 *Teaching in Interdisciplinary Contexts*

Interdisciplinary contexts and teaching methods from different disciplines may allow students to obtain a broad general knowledge base that enables them to be more capable of adapting to change.¹¹ Understanding socio-scientific issues, in addition to core chemistry concepts, requires knowledge from fields such as economics, ethics, geopolitics, and other social sciences.

Like all instructors, those teaching chemistry courses must make decisions about which topics they will teach and at what depth. Such decisions can be difficult, because the addition of information in one place may mean content deletion in another. Furthermore, chemical scenarios situated in interdisciplinary contexts often change over time, thus requiring that instructors periodically update their materials. Instructors who today engage their students in learning interdisciplinary issues will be preparing the next generation of teachers to do the same. Students, their communities, and their future employers all can reap the benefits of a broader education with sustainability-related content. In the short term, however, chemistry instructors may lack the confidence to stretch beyond core chemistry content

and will have an increased workload as they strive to master content that they themselves have never been taught.

For sustainability and interdisciplinary content to be incorporated into chemistry courses, frameworks for innovation will need to be devised and resources created to support student learning. As noted in Chapter 1, instructors cannot simply “add sustainability and stir”. Rather, this addition requires the integration of diverse perspectives, new contexts, new tools or frameworks, and societal interaction to deal with socio-scientific issues. It has already been argued that socio-scientific issues are best understood in this light.¹² Notably, the connections between chemistry and sustainability are often cast in terms related to socio-scientific issues. Because the interests of students vary greatly, the responsibility for choosing which socio-scientific issues to teach rests primarily in the hands of instructors. They will need opportunities to explore connections and assess the accuracy of the underlying science of these issues.

10.1.2.3 Creating Opportunities for Collaborative Learning

Collaborative learning has been the subject of scholarly studies for many years^{13,14} and teachers in science and math have often implemented strategies to encourage collaboration among their students.¹⁵ Given this robust history, the prospect for continued value of a focus on collaboration in teaching and learning is among the more predictable of future scenarios. In addition, the previous observations related to the increase in complexity of content that has significant interdisciplinary components bolsters the utility of collaborative efforts in the classroom. Studies have found that among the characteristics that influence learning within a group, task complexity is important.^{16,17} The advantage of group work over individual efforts tends to scale with the level of complexity of the assigned task.

The increase in interdisciplinary components that will need to be incorporated in the chemistry classroom of 2050 is the type of curricular change that ramps up complexity. There have been several educational activity resources described in this book. When these activities increase the challenges students face in learning the content, the incorporation of collaborative learning strategies may play a decisive role in creating successful learning outcomes.

10.1.2.4 Leveraging Artificial Intelligence

Artificial Intelligence (AI) will play an important role in future educational approaches to integrate sustainability into the chemistry curriculum. AI products and tools provide access to vast quantities of information that may, in principle, help to identify solutions to complex tasks. To the extent that AI systems will advance but remain constrained by the size and quality of training databases, classroom activities will be needed that ask students to apply critical thinking as they evaluate connections made by AI between chemistry and sustainability. Furthermore, as discussed in Chapter 1, generative AI can advance sustainability through catalyzing innovation,

identifying risks and investment opportunities, enhancing accountability and transparency and reshaping how society views sustainability. The meaningful development of AI and technology in chemistry education must enable students, for example, to view chemistry and chemical processes by zooming in and out of different scales, and to view chemical processes and their interactions in different science/Earth contexts.

A challenge for educators is how to help students discern the key aspects of both chemistry and sustainability, as generative AI tools make wording/writing tasks easier to accomplish. This likely future will create a need for educators to engage students with critical thinking about the outputs they receive from AI queries. This type of critical thinking is arguably custom made to foster student metacognitive awareness because they will need to monitor their thoughts of how they are approaching the vast capabilities of generative AI. Teachers will need to be able to step in when students become over reliant on the content delivered by the AI tools that will exist in the future. There will be a need to help students see how information about various context-rich examples and case studies can enhance their understanding of both factual content and the implications of that content for sustainability. As such, the examples of these types of real-world issues presented throughout this book could be used with generative AI tools to build experiences that enhance the ability of students to gain awareness of their intellectual approaches to issues of significant societal concern.

10.1.2.5 Fostering Student Agency and Stewardship

Additional guideposts for future predictions have arisen in the context of environmental education¹⁸ and the awareness of sustainability associated with the United Nations' decade of Education for Sustainable Development from 2005–2014.¹⁹ Societal transformations to address sustainability challenges will require novel approaches and instructors who can inspire a sense of agency for sustainability among students.²⁰ Enhancing the systems thinking capacity of students can have an important effect on their beliefs about global challenges.²¹

Chapter 9 emphasizes that integrating sustainable development into chemistry is valuable to drive student agency. This approach can help students set goals, use reflective practices, and act responsibly to influence societal and personal actions related to the environment. With these in mind, students can frame sustainability in such a way as to maintain their vision of a desirable future. Environmental stewardship and an emerging comprehension of sustainability principles, social equity, and economic viability are core to education for sustainable development.

10.2 Navigating Complexity: Visualizing the Teaching of Sustainability in Chemistry

To predict the changes likely to occur when incorporating sustainability into chemistry teaching, both science and learning theory need to be addressed.

Equally important is to recognize and understand how different educational drivers interact. If a broad interest in sustainability-infused chemistry education is to emerge, the connections between components need to be explored. From here on forward, these components are referred to as subsystems that contribute to the larger complex system of factors that can influence chemistry education 25 years from now. A key visualization tool for understanding complex systems comprised of subsystems, called a System-Oriented Concept Map Extension (SOCME), was described in Chapter 4 and here we discuss how one such SOCME might be constructed to summarize some of the factors that contribute to imagining the future of chemistry education.

10.2.1 Possible Subsystems

The chemistry education system we are considering for this discussion contains seven subsystems: Chemistry Foundation, Complexity, Cognitive Competencies, Technology and Society, Societal Characteristics, Sustainability Frameworks, and Convergence of scientific approaches to earth and societal challenges. Segmenting the factors that influence the trajectory from 2025 to 2050 in chemistry education into these definable subsystems offers a way to start building the complex picture shown in Figure 10.1.

This figure represents a high-level view of these subsystems, all of which can be expected to contribute to future efforts to merge sustainability concepts with chemistry content for teaching and learning. Other subsystems could certainly be proposed, but this set will serve as an organizational scaffold for the discussion here. The placement of convergence at the center is noteworthy because it explicitly emphasizes that the integration of knowledge and ways of thinking (multidisciplinary approaches) are needed to deal with complex challenges and to propose innovative solutions.

A 2014 report by the US National Academy of Sciences described convergence as an expanded form of interdisciplinary research, noting that “physical and biological sciences can each benefit from being more fully integrated into the intellectual milieu of the other”.²² Although the report’s title singles out STEM disciplines, the authors also expand their discussion into other spheres of human endeavor needed to build a convergence approach, including “economic, social, and behavioral sciences, arts and humanities disciplines”.

10.2.1.1 *The Science-centered Set of Subsystems*

Various connections are possible for any and all of the subsystems noted in the overall high-level view. However, when zooming into a subsystem, we can consider science concepts that are important when connecting chemistry and sustainability instruction. When considering the future role of chemistry in addressing sustainability issues, students must have an adequate chemistry foundation and knowledge about core chemistry ideas to evaluate the risks and benefits of chemicals and their role in socio-scientific issues.

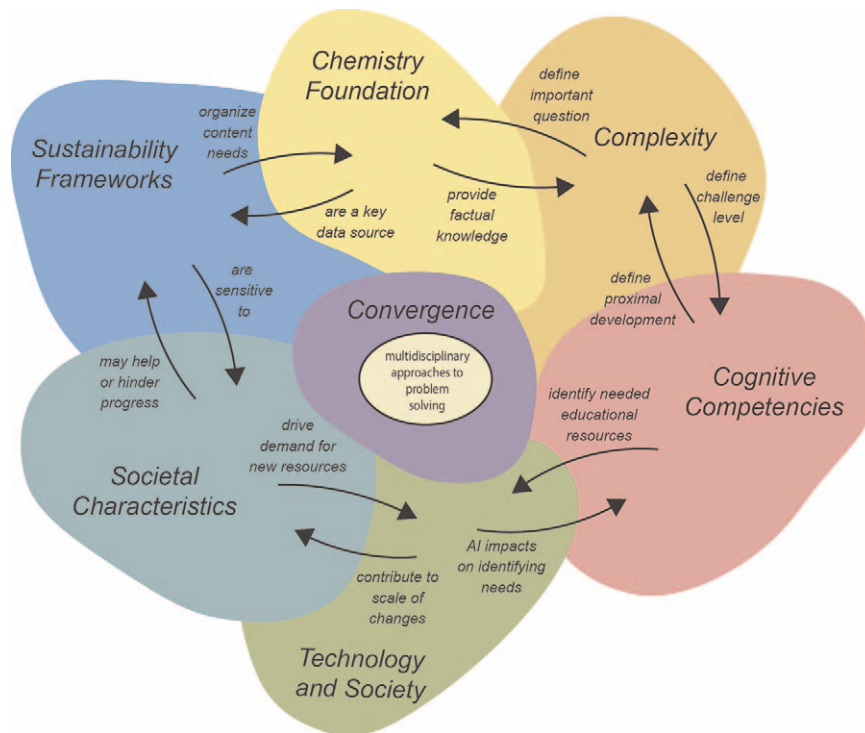


Figure 10.1 A SOCME showing high-level relationships among selected subsystems likely to influence the educational landscape in 2050.

These connections are mapped out in the Chemistry Foundation SOCME subsystem, as shown in Figure 10.2. The more detailed connections and propositions within the subsystems are representative but not exhaustive of ideas that can inform future innovation in teaching and learning.

The complexity subsystem is important to include in this grouping because incorporating sustainability will certainly increase the number of complex and uncertain examples for applying conceptual models from chemistry. Thus, the need for chemistry to provide the molecular basis of sustainability^{1,23} is strongly coupled with the complexity of sustainability challenges. To help address complex challenges, foundational knowledge in chemistry will need to include concepts not typically found in curriculum or textbook materials. Even though student understanding of risks and benefits has been studied,²⁴ it is not a particularly common feature in introductory-level textbooks.

The foundational chemistry subsystem highlights this content among many possible choices precisely because it represents a tweak in emphasis that nonetheless retains core chemistry-related skills for using quantitative information in sense-making about the field. Thinking about quantity in chemistry can be achieved with mass-based metrics, which often lack

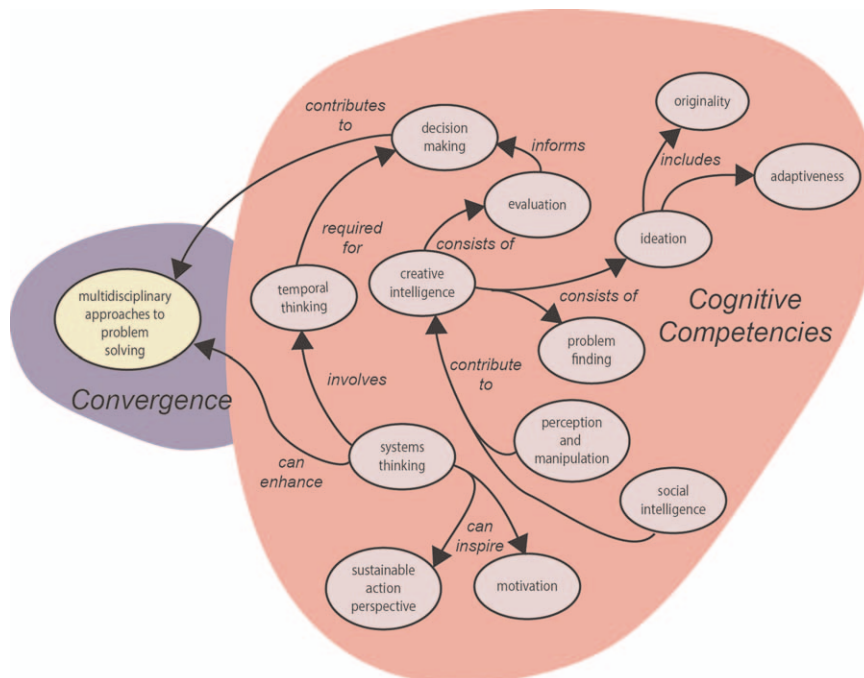


Figure 10.3 A visual exploration of various cognitive challenges for learners that arise when content domain complexity is prominent.

cognitive competencies will be an integral part of humanity's future contribution to dealing with sustainability challenges. Some of these competencies and skills connected to convergence can have significant value in chemistry education. These are organized as a separate subsystem, shown in the Cognitive Competencies SOCME subsystem in Figure 10.3.

Several key components in this example of cognitive processes may be brought to bear in dealing with complex challenges. Relative to discussions in prior chapters of this book, for example, several authors have noted the role of enhancing systems thinking skills as a key component of their discourse. Systems models make direct connections to the type of approaches needed for convergence in problem-solving strategies. Chapter 4 thoroughly discusses the pertinent skills for systems thinking approaches, including the importance of factors such as temporal thinking. This higher-order cognitive skill involves thinking about how past actions affect current system behaviors and how current actions might influence future behavior.^{28,29}

Additional cognitive components that seem likely to be important areas of development over the next 25 years are creative and social intelligence. Creative intelligence involves critical thinking approaches (problem-finding, ideation, and evaluation) to deal with important challenges.³⁰ These abilities, which are also tied to metacognition, are needed to decide on creative problem-solving efforts and to judge their outcomes with the appropriate level of

accuracy. Sustainability solutions will need to be sensitive to populations that are most vulnerable to the impacts of the sustainability challenges that have emerged over the past few decades. An important consideration for including sustainability education within the chemistry curriculum lies in how convergent interdisciplinary actions can be integrated with chemical concepts. To what extent can students in 2050 be guided to understand the role of chemistry in convergent responses to sustainability challenges?

Chemistry education researchers and practitioners will need to develop the expertise to answer the above key question to move forward. It is here where social intelligence (perceptiveness, for example) is required to negotiate for multidisciplinary problem-solving approaches.³⁰ This also ties into the proposed inter- and intra-personal professional competencies as part of Redman and Wiek's framework to undertake collaborative planning and implementation for sustainability.²⁰ We must leverage chemistry to improve the quality of life not only through material means, but also in our discourse on our society's values, needs, and demands, as emphasized in Chapter 8. The importance of chemists and chemistry working within society to address societal issues will influence how progress toward sustainability plays out.

10.2.1.3 *The Societal Set of Subsystems*

The final subset of this SOCME diagram to help organize the future prediction includes the aspects that are more directly associated with societal issues and opportunities. As noted in the 2014 National Academies Report,²² such components, often outside of traditional scientific content, also have important roles to play in developing responses to sustainability challenges. Although there are many potential subsystems to consider when incorporating areas beyond formal science, the inclusion of social, political, and widespread technological factors are key concerns, as illustrated in the Societal Characteristics SOCME subsystem in Figure 10.4.

Technology opportunities could certainly occupy a larger and broader place within the overall concept illustrated by a SOCME diagram such as this one. The motivation for a more modest incorporation of this aspect is that predicting technology advances over such a sizeable timeframe is particularly susceptible to inaccuracy or an incomplete picture. Still, entirely new and possibly disruptive technologies have emerged relatively frequently over the past 25 years; suggesting what they will look like in 25 years is predictably unpredictable. Similar unpredictability arises when considering the array of possible societal factors that may emerge, but having some level of incorporation of ideas related to such trends is important to include in this system map for the sake of some level of completeness.

10.2.2 **The Bigger Picture**

Having considered components of the larger system initially illustrated in Figure 10.1, it is possible to put together a more detailed SOCME showing

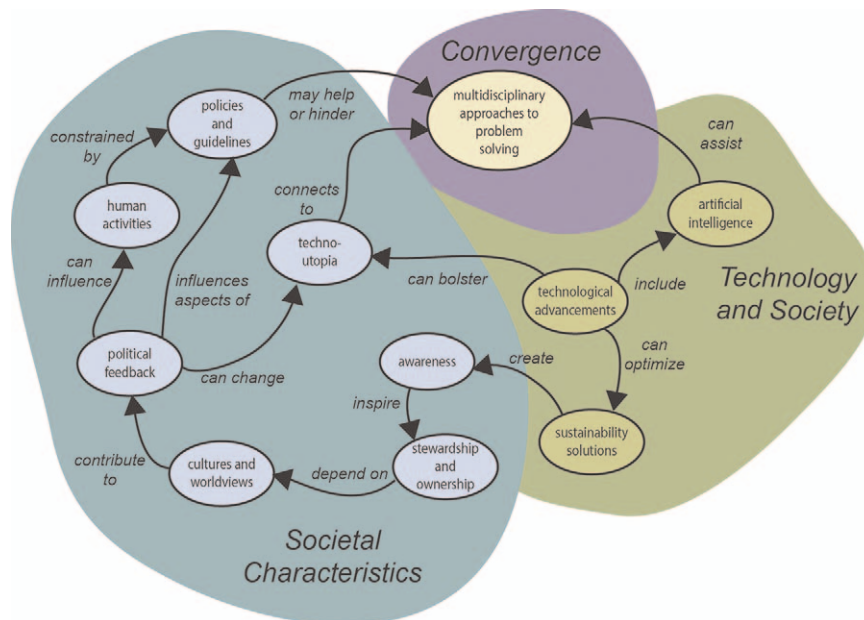


Figure 10.4 Examples of societal and technological traits that affect the teaching and learning around earth and societal sustainability.

the broad levels of connectivity at play in trying to identify a future set of possible trajectories for incorporating sustainability in chemistry teaching and learning. This overall and expanded SOCME diagram is provided in Figure 10.5. The complexity of this visualization is such that some aspects of the content in the smaller subsets have been removed to facilitate seeing the entire system.

The primary goal of including this complex diagram is to support two key ideas. First, relative to Figure 10.1, this picture has zoomed in on the content to be considered in fostering predictions of future educational innovation related to sustainability. Second, as diagrams such as SOCMEs include more components, the inherent complexity of the topic is visually striking, in addition to the specific textual characteristics of the content.

Overall, the subsystems shown in this SOCME explore the types of activities needed if sustainability issues are to be more thoroughly considered in transitioning to teach chemistry and other science topics by 2050. The choices of subsystems to include in Figure 10.5 are also meant to emphasize how some perspectives will emerge that influence curricular innovation. As 2050 approaches, featured subsystems may differ from the ones shown in the current SOCME, but a systems thinking approach will be able to identify sets of useful subsystems to include in organizing ways to contemplate creating convergent efforts for sustainability actions. Work amidst and among these subsystems points towards an interface of increasingly

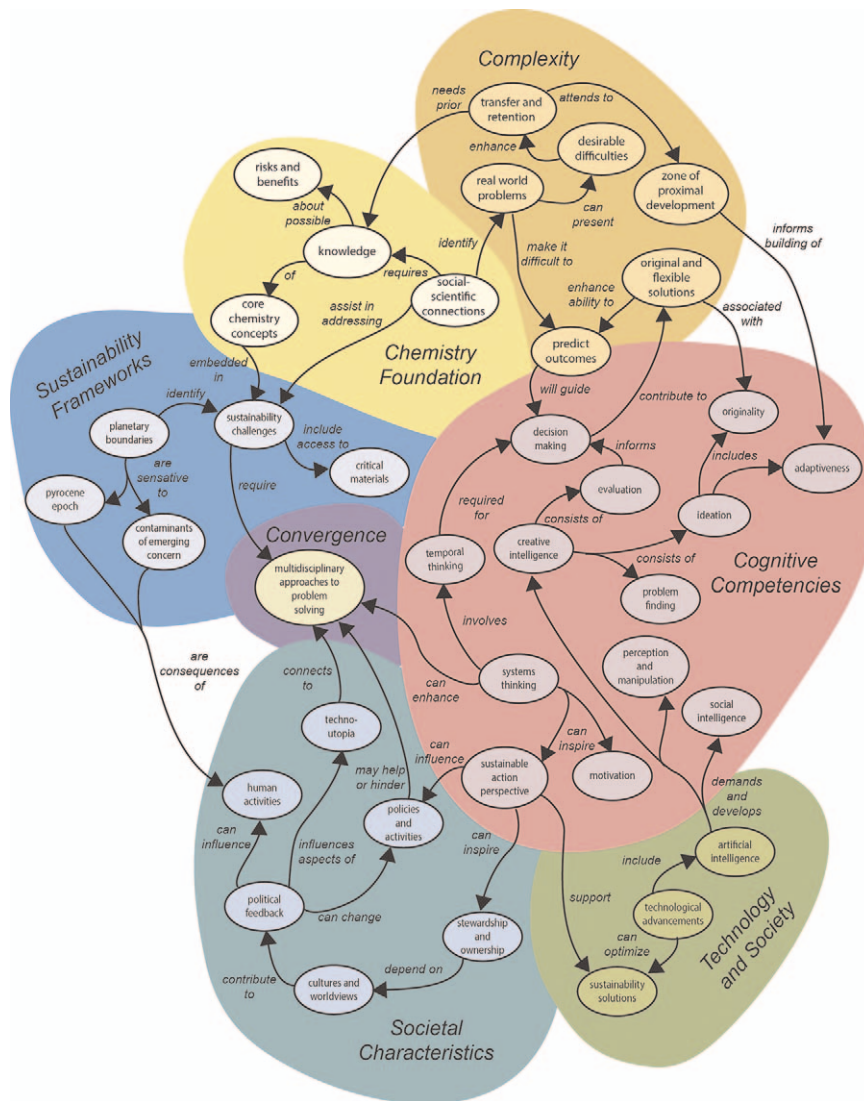


Figure 10.5 A SOCME diagram that blends the features of the previous four figures and expands on Figure 10.1 to illustrate the mixture of higher-level and more granular components of the overall system for teaching and learning complex issues, such as chemistry education contributions to understanding sustainability.

intertwined societal challenges and the ability to address them *via* core science understandings such as those presented through the study of chemistry.

Given the overarching analysis of how people learn and what conceptual knowledge will influence future developments, we have identified that

convergence and artificial intelligence will play an ever-increasing role in the future trajectory of chemistry education.

10.3 The Role of Artificial Intelligence

Some form of artificial intelligence (AI) will be involved in advancing innovation in education. Although the timing and pace of change induced by AI is uncertain, assuredly there will be barriers.³¹ In the context of chemistry education, what are these barriers? Those listed in Box 10.1 are likely to influence future accomplishments of Generative Artificial Intelligence (Gen-AI).

Although it is reasonable to expect that research will improve the technical aspects of Gen-AI models, these tools will have multiple possible mechanisms for incorporating scientific ideas into the models. Model-building involving Large Language Models (LLMs) should be large, accurate, and robust for the relevant content. How might this requirement for model training resources be influenced by intentional efforts to support the connections between chemistry and sustainability? Is it desirable, or even possible, to work towards custom LLMs with enough education-oriented

Box 10.1 Barriers emerging for Generative Artificial Intelligence (Gen-AI).

1. **Lack of AI expertise.** Although there are many novice users of Gen-AI, the number of users who are unleashing the full capabilities of the technology, including within education, is more limited.
2. **Computational power and resources.** As training sets become larger, the need for much larger computational resources becomes more acute.
3. **Explainability and interpretability.** The level of complication associated with generative AI algorithms present challenges for users to trust results from codes they do not understand.
4. **Ethical concerns.** Worries about biased results or the generation of realistic but fake materials could lead to barriers for use of Gen-AI.
5. **Attacks by adversaries.** For large language model generative AI, it is possible for adversaries to manipulate the databases used for training that could lead to undesirable results.
6. **Legal and regulatory concerns.** The ability for legal systems to keep up with the rapid changes inherent in Gen-AI may lead to opportunities for those who intend harm from malicious manipulation of Gen-AI models.
7. **Transferability and generalization.** Gen-AI models tend to train on specific domains and porting results from that domain to others can present challenges.

narratives to support the model with viable exemplars using robust science and pedagogies?

Important chemistry topics have been helpfully connected to societal challenges and offer promising possibilities for fruitful application of custom LLMs. Acid–base chemistry and combustion, and the ways they have been connected to issues related to sustainability over the past several years, provide illustrative information. Ocean acidification has been the subject of numerous educational innovations in teaching chemistry and even a small sample of articles^{32–38} reveals the variety of publication venues to be substantially interdisciplinary. The increased frequency and destructive potential of wildfires connects to combustion, though with far fewer detailed studies in the literature.^{39–41} The connections between combustion and sustainability are occasionally made, but they tend towards engineering human use of combustion in the burning of fossil fuels. Developing these and other examples show how the promise and challenge of resource generation for sustainability teaching in chemistry may produce benefits in the classroom and contribute to the future refinement of LLM models about the topic.

Large Language Models for Generative AI such as ChatGPT have shown rapid improvement and are predicated on training with large databases. This approach creates a chatbot experience that leverages the speed with which information can now be accessed and algorithmically distilled by the AI software. As such, the premise for model building is one that requires vast databases and computer resources. It is worth noting that chatbot technology more broadly speaking has been in use for many years before the emergence of generative AI chatbots more recently. These older chatbot tools incorporate machine learning within content that has been chosen for a more narrowly defined purpose and information sources curated by content experts who are responsible for their creation.

Curated chatbots are built initially using “decision trees” that organize the content and connections among sub-domains important for understanding them.⁴² This approach provides opportunities to create a well-designed automated system where resources are organized into sections. These cleverly created frameworks are useful for organizing societal sustainability challenges that students can engage with. Chatbots have been developed and tested to enhance student understanding of the connections between chemistry and sustainability.^{42,43} Chatbots can support writing assignments requiring students to make connections between general chemistry and metrics, socio-scientific issues and sustainability frameworks, including the United Nations (UN) Sustainable Development Goals (SDGs) and the Planetary Boundaries.

An extensive web of connections between general chemistry topics and the Planetary Boundaries has been created.²⁷ These efforts are noted in Chapter 6, along with examples of how eight core chemistry topics can be mapped onto Earth system processes, which can be used to teach chemistry and climate science with the Planetary Boundaries framework. This framework

embedded in the curated chatbot could help instructors identify relevant connections by bringing a local content example into the larger picture. For example, if an instructor wants to develop material related to nitrate loading in watersheds, the connection within the Planetary Boundaries framework could be made to biogeochemical flows. All connections to biogeochemical flows in the machine learning system can be leveraged.

The seventeen SDGs could be explored as a framework to engage molecular-level learning in socio-environmental problems. As discussed in Chapter 7, using SDGs and the topic of plastics during instruction can link to systems thinking, green chemistry, and sustainable chemistry with a central learning outcome emphasizing the critical role of chemistry technology in making progress towards the SDGs. Apart from these sustainability goals, these connection-building tools can be imagined for additional frameworks that emerge over the next two decades. Although not currently available, imagine an open-source resource where educators interact with these frameworks by noting specific connections. Chatbots as a style of machine learning could be valuable to mesh chemistry and sustainability in educational settings by 2050.

Rapid advances in large language models may well outpace other machine learning technologies and thereby play a larger role in directing the future of artificial intelligence. Chemistry content knowledge specialists and educators who can provide high-quality textual resources will be required as efforts to apply generative AI in complex systems with needs for convergent approaches are considered. This need can help direct student engagement with AI to support sustainability incorporation in science classrooms. One trajectory to imagine the future of chemistry and sustainability education in 2050 is to contemplate the best ways to build collaborations between chemistry educators and scientists from a broad range of sustainability-related fields. This, again, emphasizes the important role of working together for future decision-making in a convergent society.

10.4 The Role of Convergence

In simple terms, convergence is an approach to problem-solving that integrates knowledge, tools, and ways of thinking across disciplinary boundaries.²² It aims to converge expertise necessary to address a set of problems and to form a web of relationships to support scientific exploration and advance innovation. In this context, convergence as an approach can help deal with the accelerating changes to the planet. To illustrate this, changes due to growing energy demands and increasing human activities require chemistry solutions and multidisciplinary efforts. Chapter 2 discussed the Terawatt Challenge and the role of chemistry, along with other societal and political stakeholders, in the process of capturing, transporting, optimizing, and storing energy.

Other examples in Chapter 2 and from the lithium-ion battery industry (Chapter 4) highlight the need for chemists to embrace systems thinking and

cross-disciplinary working skills to consider the sustainability of material supplies, the energy costs associated with production, the environmental footprint, the material circularity, and the socio-economic challenges associated with material stewardship.

In chemistry, an integrated curriculum that includes project-based learning with interdisciplinary real-world inquiry could enable students to apply concepts and creative big-picture thinking.¹¹ Multidisciplinary, interdisciplinary, and transdisciplinary teaching (MITT) activities in higher education not only help students integrate knowledge from various disciplines but also foster metacognitive awareness, assisting the learning process.¹¹ This approach could inspire a sense of agency as students apply critical thinking and develop foresight to recognize ethical challenges and potential consequences of chemistry.

Convergence is more than a multidisciplinary collaboration; it demands all relevant areas of human and machine capability that can answer questions to solve societal issues that isolated competencies, knowledge, and technologies cannot solve.⁴⁴ Successful convergence has the following essential cultural and structural elements:²²

- i. Leaders who build strong foundations of expertise and are committed to communicating across a breadth of areas.
- ii. Organizations with appropriate structures at the frontiers of knowledge that are willing to take risks and learn from failures.
- iii. A culture that welcomes a diversity of perspectives and that supports mutual respect across disciplines.
- iv. An ecosystem that includes dynamic interactions with multiple partners within and across institutions.

A key prediction for imagining the connections between chemistry and sustainability for students is that success in this arena will be preceded by success connecting chemistry teachers at many levels with front-line scientists seeking solutions to societal-level challenges. Today's society needs teachers willing to deepen their foundational knowledge but who can engage students in broad topics, who are willing to take risks to incorporate sustainability and who can utilize pedagogical tools and artificial intelligence in their chemistry classrooms to drive future innovation. What small or large steps can you take as an educator in 2025 to help your students develop into leaders within a converging ecosystem, shaping the future of chemistry 25 years from now?

10.5 Influencing an Unpredictable Future

In the end, the ability to predict the shape of chemistry education in 2050 is, more likely than not, a fool's errand. Nonetheless, the potential associated with imagining chemistry classrooms in 25 years merits serious and reasoned investigation. Based on the modest level of impact of current efforts to

address key issues such as climate change or the integrity of the biosphere and its inhabitants, there is a need to regularly reassess the extent to which educational innovations are responding to Earth and societal challenges. Such innovations will require teams of scientists, engineers, and other experts to develop convergent solutions to large and complex problems. What then is the educational system that is needed to produce the personnel who can operate efficiently within this demanding environment?

This framing question helps point towards learning approaches that will enable chemistry students to contribute to convergent science teams. Pedagogical approaches, such as inquiry-based projects, problem-based learning, design-based thinking, and hands-on experience with real-world issues have been implemented in STEM disciplines to inspire discovery-inclined mindsets and problem-solving skills.⁴⁵ In chemistry, problem-and-research-based approaches have been used to teach students about the inter-disciplinary real-world applications of chemistry. For example, students can consider the pharmaceutical industry and the development of natural or synthetic drugs and their medical applications (pharmaceutical formulation, diagnosis, and therapy). System-oriented concept mapping activities (building SOCMEs) could be implemented to guide student exploration of the life cycle of pharmaceuticals. In one such activity, students investigated the drug Cytarabine and its core chemistry, biochemistry, side effects, discovery, economics, and ethics.⁴⁶ Using this connection-building tool enabled students to visualize the connections to topics from various disciplines that incorporate rich contexts, which further cultivates peer discussions.

System mapping activities and project- or lab-based experiences can actively engage students in learning about the chemicals most commonly used today. Students can investigate commonly used surfactants in laundry-detergent,⁴⁷ nitrogenous compounds derived from ammonia used in producing fertilizers,⁴⁸ and plastics and polymers, including polystyrene and bioplastics.^{49–51} There are numerous resources available for implementing systems thinking, including design activities, computer simulations, systems modeling, chemistry experiments, workshops, and games, all of which help students make connections, particularly to green chemistry and sustainable development.⁵⁰ Future pedagogical efforts must consider the rise in contaminants of emerging concern (CEC) such as forever chemicals (PFAS, see Chapter 3), micro-and-nanoplastics, pharmaceuticals and personal care products (PPCP), and endocrine-disrupting chemicals (EDCs). The IUPAC Systems Thinking in Chemistry for Sustainability (STCS-2030+) project has created a website, Sustainability and Systems Thinking in Chemistry Education (SaSTICE) to provide resources and tools, as well as an educational framework with examples, to help the chemistry education community incorporate systems thinking and sustainability into teaching and learning.⁵²

These ideas will need continuous refreshing by 2050 and it is vital that new approaches emerge over the next two decades. Educators will need persistence and a sense of risk/reward thinking. The question being asked is not “Will there be life on Earth in 2050, or 5050 for that matter?”, as the

answer given the evolutionary record of the planet is quite likely “yes”. The question that needs consideration is “What must humanity do to sustain the life-giving resources of Planet Earth?”

Even when societal impressions of science and the conclusions it reaches are unflattering, chemistry educators must focus on multidisciplinary solutions to address the most pressing sustainability needs. The details of what students in a chemistry classroom in 2050 will see beyond core concepts such as chemical bonding, reactions, energetics, and kinetics will gain new and increasing importance. We predict that the role of connecting chemistry, its sister sciences, and the role of sustainability will become a motivating goal for the inhabitants of this precious planet.

The time to begin is now.

References

1. P. G. Mahaffy, S. A. Matlin, T. A. Holme and J. MacKellar, *Nat. Sustainability*, 2019, **2**, 362.
2. J. D. Bransford, A. L. Brown and R. R. Cocking, *How People Learn, Brain, Mind, Experience, and School*, National Academy Press, Washington, DC, 2000.
3. J. H. Flavell, *Am. Psychol.*, 1979, **34**, 906.
4. D. F. Treagust, *Int. J. Sci. Educ.*, 1988, **10**, 159.
5. M. B. Nakhleh, *J. Chem. Educ.*, 1992, **69**, 191.
6. T. L. Nahum, A. Hofstein, R. Mamlok-Naaman and B. D. Ziva, *Chem. Educ. Res. Pract.*, 2004, **5**, 301.
7. L. Lieber and N. Graulich, *J. Chem. Educ.*, 2020, **97**, 3731.
8. J. Butler, G. Mooney Simmie and A. O’Grady, *Eur. J. Teach. Educ.*, 2015, **38**, 300.
9. J. Shen, O. L. Liu and S. Sung, *Int. J. Sci. Educ.*, 2014, **36**, 1773.
10. L. B. Armstrong, L. M. Irie, K. Chou, M. Rivas, M. C. Douskey and A. M. Baranger, *Chem. Educ. Res. Pract.*, 2024, **25**, 115.
11. J. G. Hardy, S. Sdepanian, A. F. Stowell, A. D. Aljohani, M. J. Allen, A. Anwar, D. Barton, J. V. Baum, D. Bird, A. Blaney, L. Brewster, D. Cheneler, O. Efremova, M. Entwistle, R. N. Esfahani, M. Firlak, A. Foito, L. Forciniti, S. A. Geissler, F. Guo, R. M. Hathout, R. Jiang, P. Kevin, D. Leese, W. L. Low, S. Mayes, M. Mozafari, S. T. Murphy, H. Nguyen, C. N. M. Ntola, G. Okafo, A. Partington, T. A. K. Prescott, S. P. Price, S. Soliman, P. Sutar, D. Townsend, P. Trotter and K. L. Wright, *J. Chem. Educ.*, 2021, **98**, 1124.
12. T. D. Sadler, *Stud. Sci. Educ.*, 2009, **45**, 1.
13. T. J. Nokes-Malach, J. E. Richey and S. Gadgil, *Educ. Psychol. Rev.*, 2015, **27**, 645.
14. X. Yang, *TechTrends*, 2023, **67**, 718.
15. M. Burns, E. Pierson and S. Reddy, *Int. J. Instr.*, 2014, **7**, 17.
16. A. Almaatouq, M. Alsobay, M. Yin and D. Watts, *Proc. Natl. Acad. Sci. U. S. A.*, 2021, **118**, e2101062118.

17. G. Yao, J. Wang, B. Cui and Y. Ma, *Humanit. Soc. Sci. Commun.*, 2022, **9**, 282.
18. D. Tilbury, *Environ. Educ. Res.*, 1995, **1**, 195.
19. UNESCO, United Nations decade of education for sustainable development (2005–2014): International implementation scheme, <https://unesdoc.unesco.org/ark:/48223/pf0000148654> (accessed August 2025).
20. A. Redman and A. Wiek, *Front. Educ.*, 2021, **6**, 5.
21. M. T. Ballew, M. H. Goldberg, S. A. Rossenthal, A. Gustafson and A. Leiserowitz, *Proc. Natl. Acad. Sci. U. S. A.*, 2019, **116**, 8214.
22. National Research Council, *Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering and Beyond*, National Academies Press, Washington, DC, 2014.
23. P. T. Anastas and J. B. Zimmerman, *Chem*, 2016, **1**, 10.
24. S. Cullipher, H. Sevia and V. Talanquer, *Chem. Educ. Res. Pract.*, 2015, **16**, 377.
25. J. Rockstrom, W. Steffen, K. Noone, A. Persson, F. S. Chapin, E. F. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. J. Schellnhuber, B. Nykvist, C. A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sorlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen and J. A. Foley, *Nature*, 2009, **461**, 472.
26. W. Steffen, K. Richardson, J. Rockstrom, S. E. Cornell, I. Fetzer, E. M. Bennett, R. Biggs, S. R. Carpenter, W. de Vries, C. A. de Wit, C. Folke, D. Gerten, J. Heinke, G. M. Mace, L. M. Persson, V. Ramanathan, B. Reyers and S. Sorlin, *Science*, 2015, **347**, 736.
27. R. P. MacDonald, A. N. Pattison, S. E. Cornell, A. K. Elgersma, S. N. Greidanus, S. N. Visser, M. Hoffman and P. G. Mahaffy, *J. Chem. Educ.*, 2022, **99**, 3530.
28. O. Assaraf and N. Orion, *J. Res. Sci. Teach.*, 2005, **42**, 518.
29. M. Orgill, S. York and J. MacKellar, *J. Chem. Educ.*, 2019, **96**, 2720.
30. T. A. Holme, *J. Chem. Educ.*, 2019, **96**, 611.
31. Reznikov R., Leveraging Generative AI: Strategic Adoption Patterns for AI, <https://ssrn.com/abstract=4851632> (accessed August 2025).
32. K. D. Gorospe, B. K. Fox, R. D. Haverkort-Yeh, C. S. Tamaru and M. A. Tivera, *J. Geosci. Educ.*, 2013, **61**, 396.
33. K. I. Danielson and K. D. Tanner, *CBE—Life Sci. Educ.*, 2015, **14**, ar29.
34. J. M. Buth, *J. Chem. Educ.*, 2016, **93**, 718.
35. A. Moon, R. Moeller, A. R. Gere and G. V. Shultz, *Chem. Educ. Res. Pract.*, 2019, **20**, 484.
36. A. Z. Roche, A. D. Shrode, J. Gonzalez, A. Rose, A. I. Green, U. Swamy, R. L. Matz and S. M. Underwood, *J. Chem. Educ.*, 2022, **99**, 2182.
37. A. W. Wisudawati and H. D. Barke, *Sustainable Chem. Pharm.*, 2024, **37**, 101384.
38. W. P. Hall and K. Cantrell, *J. Chem. Educ.*, 2024, **101**, 3922.
39. J. Sjöström, F. Rauch and I. Eilks, in *Relevant Chemistry Education*, Brill, Leiden, Netherlands, 2015, p. 163.

40. P. Dishadewi, A. Wiyarsi, A. K. Prodiosantoso and A. R. Nugraheni, *J. Phys.: Conf. Ser.*, 2020, **1440**, 012007.
41. L. M. Mata and J. Liu, in *Chemistry Education for a Sustainable Society Volume 2: Innovations in Undergraduate Curricula*, American Chemical Society, Washington DC, 2020, p. 93.
42. A. T. Lolinco and T. A. Holme, *J. Chem. Educ.*, 2023, **100**, 4092.
43. A. T. Lolinco and T. A. Holme, *J. Chem. Educ.*, 2024, **101**, 4837.
44. W. S. Bainbridge and M. C. Roco, *Handbook of Science and Technology Convergence*, 2015.
45. M. Ammar, N. J. Al-Thani and Z. Ahmad, *Soc. Sci. Humanit.*, 2024, **9**, 100839.
46. T. A. Holme, *Sustainable Chem. Pharm.*, 2020, **16**, 100234.
47. M. Reynders, L. A. Pilcher and M. Potgieter, *J. Chem. Educ.*, 2023, **100**, 1357.
48. P. G. Mahaffy, S. A. Matlin, J. M. Whalen and T. A. Holme, *J. Chem. Educ.*, 2019, **96**, 2730.
49. A. Jackson and G. A. Hurst, *Chem. Educ. Res. Pract.*, 2021, **22**, 855.
50. A. M. Ward and G. R. A. Wyllie, *J. Chem. Educ.*, 2019, **96**, 668.
51. E. K. Morasae, Z. L. R. Botterell, S. H. V. Andrews, N. Beaumont, P. Boisseaux, H. Chadwick, R. Cherrington, M. Cole, R. L. Coppock, K. Deakin, E. M. Duncan, D. Flor, T. S. Galloway, S. L. Garrard, B. J. Godley, D. Harley-Nyang, C. Lewis, P. K. Lindeque, P. McCutcheon, R. Nolan and S. E. Nelms, *J. Environ. Manage.*, 2024, **371**, 122994.
52. International Union of Pure & Applied Chemistry, Systems Thinking in Chemistry for Sustainability: Toward 2030 and Beyond (STCS 2030+), IUPAC Project No. 2020-014-3-050, <https://iupac.org/project/2020-014-3-050> (accessed August 2025).

Subject Index

Figures appear in *italic*; tables in **bold**

Abbreviations

ChEMIST = Characteristics
Essential for designing or
Modifying Instruction for a
Systems Thinking approach
KCVS = King's Centre for
Visualization in Science
PFAS = perfluoroalkyl and
polyfluoroalkyl substances
SOCME = Systems Oriented
Concept Map Extension
UN SDGs = United Nations
Sustainable Development Goals

accidents, chemical 68–69

Acids and Bases module, systems
thinking 104–106

activities for students

carbon cycle 22–24

ChEMIST table 103–106

Earth's material resources
39–42

endangered elements 44–48

future of chemistry education
253

impact based metrics 147–153

material circularity 49–57

PFAS 87–89

planetary boundaries 170–180

plastics and polymers, UN
SDGs 199–209

refrigeration 227

visualization techniques/
reaction subsystems
114–128

aerosol optical depth 172

agency-centered sustainability
education 239
interview questions **240**

Agenda for Sustainable Development
2030 216, 236

albedo, Earth's 171, 173, 175–176

aluminium 50–52

American Chemical Society

Campaign for a Sustainable
Future 196

Green Chemistry Institute 128,
197, 222

ammonia synthesis 194, 195

Anastas, Paul T. 8

aniline 68

Anthropocene 3, 199; *see also* human
impacts

anthropogenic mass increase 30

anthropogenic nitrogen cycle 128,
197

artificial intelligence 13–16

future of chemistry education
255–256

Large Language Models
264–266

Association for the Advancement of
Sustainability in Higher
Education (AASHE) 190

atmospheric aerosol loading 172

atmospheric lifetime, greenhouse
gases 179

- atmospheric ozone depletion 146, 227
- atom economy 136–138
- BASF (multinational company) 187
- battery electric vehicles 108
- carbon footprint 111
- bauxite mining 51
- Bhopal disaster 69
- biochemistry 228–229
- biodiversity loss 160
- biological processes 16
- biomass
- vs. anthropogenic mass 32
 - as substitute for fossil fuels 37
- biosphere integrity 160, 169
- biosystems of the planet 36–39
- Boulding, Kenneth 32
- Brundtland Commission 4
- Buckminster Fuller, Richard 32
- Build a Planet Learning Tool (KCVS) 171–172, 173
- cadmium poisoning 70
- Campaign for a Sustainable Future (American Chemical Society) 196
- “campus sustainability map” project 239–243, 241
- design principles 246–248
- carbon cycle 17–19, 18, 19; *see also* greenhouse gases
- activities for students 22–24
 - climate change 19–20
 - connected issues **20**
 - learning outcomes 20–22
- carbon dioxide, atmospheric 33, 169–170, 244
- carbonate ions, oceanic 100–101; *see also* ocean acidification
- careers
- academia 190–191
 - chemical industry 187–190
- Carson, Rachel 67
- CFCs (chlorofluorocarbons) 70, 226–227
- Characteristics Essential for designing or Modifying Instruction for a Systems Thinking approach (ChEMIST) 97–99, **98**
- activities for students 103–106
- chatbots 264–266
- chemical elements, endangered 41–42, 44–48
- chemical processes; *see also* subsystems of chemical processes and biological processes 16
- broader impacts 106–107
 - circularity 12
 - differing scales 106, 256
 - energy efficiency 16
 - ocean acidification 100
 - planetary boundaries 181
 - scales 106
 - SOCME 115
 - sustainability in vii, 55–56, 120–124, 127
 - toxicity 12, 83
 - waste 138–139
- ‘Chemical Sector SDG Roadmap’ (WBCSD), 187
- chemical waste and accidents 68–69
- ChEMIST *see* Characteristics Essential for designing or Modifying Instruction for a Systems Thinking approach
- chemistry education in future *see* future of chemistry education
- ‘Chemistry for sustainability’ pyramid 57–59
- chemistry professional societies 196–197
- chlorofluorocarbons (CFCs) 70, 226–227
- chymotrypsin 229
- circular chemistry 11–13, 71–74, 77
- 12 Principles of 12, 72, 83
- climate change 33, 160, 181
- carbon cycle 19–20
 - control variables 169–170, **170**, 172

- climate change (*continued*)
 impact of AI 14
 Molecular Structure and Bonding core topic 166
- Club of Rome 32–33
- coal tar 68, 69
- cold chain *see* refrigerants
- collaborative learning 255
- common-use chemicals 268
- communities, needs of 2–3
- complex systems, understanding 96
- concept maps 116
- consistency, sustainability strategy 74
- consumption/production systems 50
- contamination
 contaminants of emerging concern (CEC) 186, 268
 land 53, 112
 PFAS 70–71
 water *see* water contamination
- convergence, interdisciplinary research 256, 266–267
- copolymers 198
- core chemistry topics
 Earth system processes vii, 166, 167–169, 265
 interdisciplinary contexts 254
 SOCME 107–108, 257
 systems thinking 197, 203
- core reaction subsystems 117–128, 118, 119
- cosmic dust 30, 32
- cotton
 vs. polyethylene reusable bags 136
 sustainability 52–53
- covalently bonded repeating units 198
- COVID-19 vaccines 13
- critical materials 41–42, 45, 110, 126
- curriculum, how topics connect to v, ix, 24–25
 carbon cycle 19–29
 Earth's material resources 42
- Education for Sustainable Development 246–248
 impact based metrics 143–153
 lithium-ion batteries 113–114
 material circularity and stewardship 55–57
 ocean acidification 102–103
 PFAS 83–87
 planetary boundaries 161, 165–170
 professional ethics 219–223
 UN SDGs 185, 191–197, 196
- da Vinci, Leonardo viii
- development, sustainable 74, 94, 216; *see also* United Nations Sustainable Development Goals
- dioxin 68–69
- Dow Chemical Company 187
- drug discovery, use of AI 13
- dyes, synthetic 68, 69
- Earth system processes 36–39, 159; *see also* Planet Earth
- The Economics of the Coming Spaceship Earth* (Boulding) 32
- economic subsystem, SOCME 126
- EDCs *see* endocrine-disrupting chemicals
- education *see* future of chemistry education; learning outcomes; teaching/learning sustainability
- Education for Sustainable Development (ESD) 236–237, 248–249
 case studies 239–246
 design principles 246–248
 student agency 237–239
 UNESCO 191
- E-factor* 136–138
- efficiency, sustainability strategy 74
- electricity production, impacts 154
- emergent properties (systems thinking) 94, 96, 114, 253
 sustainability 59, 106, 127

- endocrine-disrupting chemicals (EDCs) 268
- energy
 balance on Earth 158, 169, 170–174
 chemical processes
 efficiency 16
 requirements/storage/transmission 33–36
 solar radiation 33
- environmental chemistry 67, 69–71, 69–72
 characteristics 77
- environmental impacts
 chemical processes 142
 cotton 52–53
 cotton vs. polyethylene 136
 molecular design to reduce 149–150
- enzyme catalysis 228–229
- ESD *see* Education for Sustainable Development
- The Ethical Chemist* (Kovac), 223
- ethics vii, 215–217, 232
 case studies 221–223
 class discussions 230
 informal exploratory writing 230–232
 professional 217–224
 sourcing lithium 124–125
 teaching/learning
 sustainability 224–232
- Ethics of Chemistry: From Poison Gas to Climate Engineering* (Schummer and Borsen) 223
- Evagorou, M. 11
- Falkenburg, L. J. 102
- fertilizers, nitrogen 195
- first-year chemistry 136
 impact based metrics 145, 155
 Lewis structures 226
 polymers 198
 UN SDGs 192
- Flavell, J. H. 252
- Flint, Michigan water crisis 186, 222
- food vs. fuel, land use 38
- forestry 4
- forever chemicals *see* PFAS
- fossil fuels 72
- foundational chemistry knowledge 2, 20–21, 257, 259, 267
 ethics 225
 lithium-ion batteries 113
 ocean acidification 102
 PFAS 85–86
 planetary boundaries 165, 170
 UN SDGs 186, 194, 198, 209
- free radical polymerizations 198
- fuel vs. food, land use 38
- future of chemistry education viii, 78, 251–256
 role of AI 264–266
 role of convergence 266–267
 SOCME 256–264
 unpredictability 267–269
- Gardner, H. 232
- gate-to-gate life-cycle analysis 141, 152
- Generative Artificial Intelligence 264–266
- Global Chemical Outlook II* (UNEP) 187, **188–190**
- global environmental sustainability 160–165
- global systems challenge *see* planetary boundaries
- Good Chemistry: Methodological, Ethical, and Social Dimensions* (Mehlich) 216–217, 223
- Great Pacific Garbage Patch 13
- green chemistry 7–8, 81; *see also* sustainable chemistry
 characteristics 77
 pollution prevention, industry 71
 Principles of 8, 15, 55, 71, 76, 78, 82–83, 194–196
- Green Chemistry Institute (American Chemical Society) 128, 197, 222

- Green Chemistry: Theory and Practice* (Anastas & Warner) 8
- green hydrogen 37–39
- greenhouse gases, 56, 138, 177–180, 200; *see also* carbon cycle; climate change
- aluminium production 14
 - energy balance on Earth 173
 - impacts of AI 14
 - net zero goals 33
 - perfluorocarbons 51
 - plastics production and disposal 200
 - radiative forcing, Earth's 171
- greenwashing 7
- Guerra, A. 238–239
- Haber–Bosch process 116, 117, 194, 222
- Handbook on Life Cycle Assessment to the ISO Standards* (De Bruijn *et al.*) 140
- harm from chemicals, assessment 136, 139, **140**, **142**
- HCFCs (hydrochlorofluorocarbons) 146, 227
- HFCs (hydrofluorocarbons) 227
- health issues 16, 57, 69–72, 186, 218, 220; *see also* ocean acidification, water contamination
- environmental chemistry 67–71
 - HIV/AIDS 228–229
 - PFAS 81, 82–83
 - plastics 200
 - refrigeration 225
 - SOCME 123
 - UN SDGs 186
- historical perspectives
- circular economy 72
 - practicing chemistry 78
- HIV/AIDS 228–229
- How People Learn* (US National Research Council) 252
- human impacts 29–30; *see also* Anthropocene, climate change, ocean acidification
- atmospheric chemistry 159
 - global environmental sustainability 158
 - material flows 159
 - plastics 199, 200
 - population growth 30
- human-level subsystems, SOCME 124–126
- Hurst, G. A. 196
- hydrochlorofluorocarbons (HCFCs) 146, 227
- hydrofluorocarbons (HFCs) 227
- hydrogen, green 37–39
- impact based metrics vii, 135–143, 136, 259
- importance *vs.* mass-based metrics 153–155
 - learning outcomes **144**
 - teaching and learning 143–153
- Industrial Revolution 158
- interdisciplinary contexts 186, 248, 261, 266–267
- convergence 256
 - core chemistry topics 254–255
- International Union for Pure and Applied Chemistry *see* IUPAC
- IR Windows for Greenhouse Gases Learning Tool (KCVS) 178–180, 178
- International Union of Pure and Applied Chemistry (IUPAC) viii, 44, 71, 161, 166–169
- Interdivisional Committee for Green Chemistry for Sustainable Development 196
 - SaSTICE website 128, 268
 - STICE project 161
 - Systems Thinking in Chemistry for Sustainability: Toward 2030 and Beyond project 166
- Keijer, T. 11–12
- King's Centre for Visualization in Science (KCVS) 163–165

- learning tools *see* Build a Planet Learning Tool; IR Windows for Greenhouse Gases Learning Tool; Planetary Boundaries Learning Tool; Radiative Forcing Learning Tool
- Koskela, I.-M. 239
- Kümmerer, Klaus 9–10
- Large Language Models (LLMs) 264–266
- LCA *see* Life Cycle Assessment
- LDPE (low-density polyethylene) 204–206
- learning methods/processes 252–256
- learning outcomes
 - carbon cycle 20–22
 - Earth's energy balance 172–173
 - ethics 224–225
 - global environmental sustainability 161
 - greenhouse gases 179
 - impact based metrics 144, 147–149
 - periodic table 42–44
 - PFAS 85–87
 - polymers 199
 - radiative forcing 176
 - UN SDGs 210
 - visualization 162
- learning sustainability *see* teaching/learning sustainability
- Lewis structures 219, 225–227
- Life Cycle Assessment (LCA) 136, 140–143, 147, 259
 - advanced exercise 150–153
 - cradle-to-grave 141
 - Handbook on Life Cycle Assessment* 140
 - impact assessment 142–143
 - importance of impacts 155
 - peer teaching activity 147–149
- Limits to Growth* (Club of Rome) 32–33
- lithium-ion batteries 106–108
 - basic understanding 108–110
 - connections to chemistry
 - curriculum 113–114
 - key components 110
 - lithium recycling 110–113, **112**
 - lithium sources, processing and refining 110–112
 - reaction subsystems 118, 119
 - schematic 109
 - SOCME 118–119, 126
 - sustainability question 122
- lithium production, CO₂ emissions 111–112
- Love Canal disaster 68
- low-density polyethylene (LDPE) 204–206
- Mahaffy, P. G. 194
- Mamlok-Naaman, R. 237
- Mandler, D. 237
- mapping techniques 107–108
- marine organisms, ocean acidification 101
- mass-based metrics 136–138, 258–259
- materials *see* resources, material
- McClinden, M. O. 225
- Mehlich, Jan 216–217, 223, 232
- Mendeleev, Dimitri 42
- mercury poisoning 70
- metacognition 252
- metrics *see* impact based metrics
- methyl isocyanate 69
- Michigan water crisis 186, 222
- microplastics 197, 200, 268
- micropollutants 70
- Middlecamp, Cathy 242
- MITT (multidisciplinary, interdisciplinary, and transdisciplinary teaching) 266–267
- molecular design 149–150
- molecular shapes 225–227
- Molecular Structure and Bonding (core chemistry topic) 166
- molecular/material basis, sustainability, 58

- monomers, conversion to linear polymer chains 198
- multidisciplinary, interdisciplinary, and transdisciplinary teaching (MITT) 266–267
- nanoplastics 268
- National Environmental Education and Training Foundation 237
- National Science Foundation Center for Sustainable Polymers 202
- net zero goals, greenhouse gases 33
- Next Generation Science Standards (NGSS) 161
- nitrogen cycle, anthropogenic 128, 197
- nitrogen fertilizers 195
- ocean acidification 99–102
 - ChEMIST table 103–106
 - curriculum connections 102–103
 - visualization 100
- ocean debris, plastics **200**; *see also* Great Pacific Garbage Patch
- Operating Manual for Spaceship Earth* (Buckminster Fuller) 32
- organic chemistry, introductory 145
- organicallychem.com* 145
- Orgill, M. 96–97
- Our Common Future* (World Commission on Environment and Development) 216
- Our World in Danger* (website) 223–224
- ozone depletion 146, 227
- Pacific Garbage Patch 13
- packaging, single-use 203–209
- Paloniemi, R. 239
- peer reviews 195
- peer teaching activities 147–149
- perfluoroalkyl and polyfluoroalkyl substances *see* PFAS
- periodic table of the elements 40
 - endangered elements 41
 - learning outcomes 42–44
- persistent organic pollutants 81
- pesticides 222
- PETE (polyethylene terephthalate) (resin code 1) 204–206
- PFAS (perfluoroalkyl and polyfluoroalkyl substances) 69–70
 - activities for students 87–89
 - chemistry 78–80
 - chemistry topics **85**
 - future of chemistry education 268
 - human health/environmental impacts 81
 - learning outcomes 85–87
 - media coverage 186
 - products containing 79
 - sustainable chemistry 82–83, **84**
 - wider context 80–82
- pharmaceuticals and personal care products (PPCP) 268
- Planet Earth *see also* Earth system processes
 - biosystems 36–39
 - as closed system 30–33
 - as open system 33
 - system needs 3–6
- planetary boundaries, vi, vii, 120, 121, 181, 259; *see also* resources, material
 - framework 4, 5, 49
 - global environmental sustainability 160–165
 - global systems challenge 157–160
 - visualization 159
- Planetary Boundaries Learning Tool (KCVS), 163–166, 172, 173–174, 175, 177, 178, 180, 181
- plastics 196–197
 - debris in oceans, **200**
 - life-cycle approach, 202
 - nanoplastics 268
 - recycling, 13
 - resin codes, 203, **204**

- single-use **168**, 200, 209
- sustainable 201–203
- political subsystem, SOCME 126
- pollution 67
 - plastics 197, **200**, 202
 - prevention 71, 186
- polyethylene terephthalate (PETE) (resin code 1) 204–206
- polyethylene vs. cotton reusable bags 136
- poly(lactic acid) (PLA) (resin code 7) 204–208, **208**, 208
- polymers 67, 196–201
 - architectures 199
 - linear polymer chains 198
 - single-use packaging 203–209
- polyvinyl chloride (PVC) 198, 199
- population growth, over 2 millennia 30
- positive feedback loops 107
- PPCP (pharmaceuticals and personal care products) 268
- precautionary principle 74, 76
- Principles of Circular Chemistry 12, 72, 83
- Principles of Green Chemistry 8, 15, 55, 71, 76, 78, 82–83, 194–196
- production/consumption systems 50
- professional ethics 217–224
- PVC (polyvinyl chloride) 198, 199

- quantitative information 258
- quantitative structure–activity relationship (QSAR) 150

- radiative forcing, Earth's 169–170, 170–174
- Radiative Forcing Learning Tool (KCVS) 175, 176–177, 178–180
- recycling
 - aluminium 52
 - hierarchy of approaches 73
 - plastics 198
 - recycle symbol 204
- reduce, reuse, recycle campaign 48, 73

- refrigerants 225–227
- regrettable substitution 142
- renewable energy 33
- resources, material; *see also*
 - planetary boundaries
 - activities for students 39–42, 49–55
 - basic understanding 39, 39–42
 - connections to chemistry curriculum 42, 55–57
 - endangered elements 44–48
 - framework 57–59
 - learning outcomes 42–44
 - renewable resources 71
 - stewardship 48–54
- responsibility, socio-environmental 162
- Rio Declaration 71
- risk migration 142, 147
- Roser, Nax 223

- Safe and Sustainable by Design (SSbD) framework 74
- 'safe operating space for humanity' 160
- Science Education for New Civic Engagements and Responsibilities (SENCER) 219–220, 220, 222
- sensitivity analysis, life-cycle analysis 143
- Seveso disaster 68–69
- Shulman, L. S. 232
- Silent Spring* (Carson) 67
- Sindiani-Bsoul, Ayshi 244–246
- single-use packaging 203–209
- single-use plastics **168**, 200, 209
- Smalley, Richard 33
- smartphones 53–54
- smelting aluminium 51–52
- social subsystem, SOCME 125
- societal issues 3, 261, 262, 269
- socio-environmental issues viii, 162, 192, **194**, 195, 197, 266
- socio-scientific issues 38, 185, **194**, 197, 220, 237, 248, 253–5, 257

- SOCME *see* Systems Oriented
Concept Map Extension
- solar radiation/energy 33
- 'Spaceship Earth' 32
- Spaceship Earth* (Waed) 32
- "Speak to Me in Numbers" project
243–246, 244
design principles 246–248
- Stanton, Audrey 242
- Stockholm Convention 81
- Stockholm Resilience Centre 4
- stoichiometry 20, 144, 195
- student activities/projects *see*
activities for students
- student agency vii, 237–238
active participation 248
framework in sustainability
238–239
future of chemistry education
256
- student learning outcomes *see*
learning outcomes
- student misconceptions 254
- student needs 2
- subsystems of chemical processes
core chemistry topics 106–107,
253, 257–264
core reaction 117
planetary 120–122, 158–159
Haber–Bosch process 194
human-level 122–127, 124, 125
reaction 117–128, 118, 119
Sustainable Polymer
Framework 202–203, 207
- sufficiency, sustainability strategy 74
- sulfate aerosols 177
- Superfund Act 68
- sustainability
definitions/characteristics, 3–6
molecular/material basis 58
tools *see* impact based metrics
- sustainability, links with chemistry
vi, 1–2, 7–17, 24, 28–29, 66–68, 89,
171
chemical waste and accidents
68–69
- 'Chemistry for sustainability'
pyramid 57–59
- circular economy/circular
chemistry 71–74
- communities needs, 2–3
- environmental chemistry
69–71
- interrelationships 76–78
- needs of all life on planet, 3–6
- planetary impact of human
activity 29–39
- pollution prevention,
industry 71
- strategies 74–76
- teaching/learning *see* teaching/
learning sustainability
- Sustainability and Systems Thinking
in Chemistry Education (SaSTICE)
website 128, 268
- sustainable chemistry, 9–10; *see also*
green chemistry, circular
economy/circular chemistry
characteristics, 77
education requirements, 24
key characteristics, 9–10, 75–76
PFAS, 83
- Sustainable Development Goals *see*
United Nations Sustainable
Development Goals
- Sustainable Polymer Framework
(SPF) 201, 202
- synthetic organic polymers *see*
polymers
- Systems Oriented Concept Map
Extension (SOCME) 105–106, 108,
115
ammonia synthesis 194
anthropogenic nitrogen cycle
197
future of chemistry education
256–264, 268
lithium-ion batteries 118–119
planetary sustainability
120–128, 121
- systems thinking vi, 11, 39, 93–95,
128–129

- benefits, challenges, characteristics 95–99
- future of chemistry education 268
- holistic approaches 194
- IUPAC projects 161
- lithium-ion batteries 106–128
- ocean acidification 99–106
- planetary boundaries 162, 163
- Systems Thinking in Chemistry Education (STICE) project 161
- Systems Thinking in Chemistry for Sustainability: Toward 2030 and Beyond project 161, 166–169, 268
- tantalum 45, 47
- targets, United Nations Sustainable Development Goals 192, **193**
 - teaching/learning sustainability ix, 17–24, 78–89
 - chemical basis 39
 - Earth's material resources 39–48
 - ethics 224–232
 - impact based metrics 143–153
 - lithium-ion batteries 106–128
 - material circularity 48–57
 - ocean acidification 99–106
 - planetary boundaries 160–180
 - sustainable chemistry 78–89
- technological challenges 261, 262
- 'Terawatt Challenge' 33–36
- thermoplastics 198
- throw-away mentality 200, 201
- Tolkien, J. R. R. 210
- transformations
 - energy 3, 158
 - material vii, 3, 18, 29–31, 49, 67, 158, 253
 - societal 256
 - sustainable 59, 237
- Triple Bottom Line 3
- United Nations' Decade of Education for Sustainable Development 256
- United Nations Environment Programme (UNEP) 187–190, 202
- United Nations Sustainable Development Goals (UN SDGs) vi, vii, 5, 6, 129, 184–192, 185, 209–210
 - activities for students 47
 - curriculum connections 192–197
 - Education for Sustainable Development 236
 - ethics 216
 - ocean acidification 104
 - planetary boundaries 74
 - student agency 243
 - systems thinking 94
 - teaching/learning sustainability 197–209
- United Nations Educational, Scientific and Cultural Organisation (UNESCO) 191
- United States Environmental Protection Agency 7
- universal recycle symbol 204
- University of Wisconsin–Madison, USA 239–243
- upper-level chemistry courses 147
- Valence Shell Electron Pair Repulsion (VSEPR) 227
- vapor-compression refrigeration 225–226
- viruses, life-cycles 228
- visualization techniques 107–108, 114–128; *see also* Systems Oriented Concept Map Extension
- Visualizing the Chemistry of Climate Change (VC3) project 99
- von Carlowitz, Hans Carl 3–4
- Ward, Barbara 32
- Warner, John C. 8
- waste
 - biomass 38
 - chemical 7, 68, 138, 202, 218
 - electronic 43, 45, 54

- waste (*continued*)
 - management 10–12, 16, 48–49, 187, 200, 252
 - plastics 191
 - storage 122
 - water availability 36
- water contamination, 49, 53, 101–102, 200, 201, 209; *see also*
 - ocean acidification
 - Flint, Michigan water crisis 186, 222
 - life-cycle analysis 142–143
 - mercury 70
 - mining waste 122
 - PFAS 79–82
 - water purification 186, 191
- web-based resources 150, 196–197
- Weizmann Institute of Science, Israel 243–246
- Whitesides, Alan 228
- World Business Council for Sustainable Development (WBCSD) 187
- York, S. 96–97
- zinc 45, 46