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United Nations Sustainable Development Goals as a Thematic Framework for an Introductory Chemistry Curriculum

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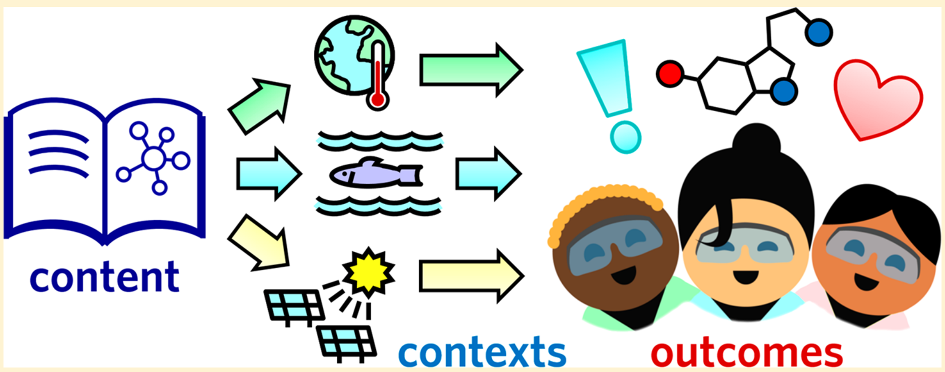
Supporting Information



ABSTRACT: As part of a revision to the content and delivery of first-year chemistry instruction at the University of British Columbia's Okanagan campus, we have employed the United Nations Sustainable Development Goals (UN SDGs) as a thematic framework. This framework was introduced to promote the achievement of affective learning outcomes, including a systems thinking approach to exploring the relevance of first-year chemistry content and concepts to societal and global challenges. Through this framework, sets of course concepts, which are traditionally limited in their application to isolated textbook chapters, are demonstrated, through various in-class group activities, to have collective applications to the environmental and societal systems embodied by specific SDGs. Student attitudes to this framework and its associated activities were examined via a course-end survey and in-depth semistructured interviews. Student responses were generally positive, indicating an appreciation for the relevance of course concepts to the global challenges described by the SDGs, and for many students, the SDG-framed learning activities aided in their understanding of course concepts.

KEYWORDS: *First-Year Undergraduate/General, Curriculum, Environmental Chemistry, Collaborative/Cooperative Learning, Inquiry-Based/Discovery Learning, Student-Centered Learning, Applications of Chemistry, Medicinal Chemistry, Systems Thinking, Sustainability*

INTRODUCTION AND CONTEXT

Although traditional science education focuses primarily on cognitive learning outcomes, there is growing understanding of the need to introduce affective learning to chemistry education.[1] In particular, many have advocated for the inclusion of meaningful individual and societal contexts for the traditional content in science education, and for the teaching and assessment of learning outcomes that demonstrate the roles of chemistry in global stewardship and creation of a sustainable society,[2−8] thereby impacting the interests, attitudes, values, and behaviors of students.

At the University of British Columbia's Okanagan Campus, we are undertaking a substantial revision of both the content and delivery of our introductory chemistry courses, which are taught as a sequence of two one-semester courses to approximately 700 to 800 students each year. In each semester, students attend approximately 32 h of classroom activities (e.g., 24 lecture periods of 80 min) and 10 laboratory sessions of 3 h each. Despite the challenges inherent in class sizes of 200−400 students,[9] our delivery model deliberately incorporates a range of active and interactive learning activities, including the use of personal response systems with peer discussion,[10] small-group (∼4 students) guided-inquiry assignments,[11] flipped-class modules,[12] directed case studies,[13] and collaborative two-stage exams.[14] Assessment comprises biweekly online quizzes, term tests, and a cumulative final exam each semester. A significant driving force for this revision has been the explicit inclusion of affective learning outcomes. Some of our learning outcomes that have affective components include the following:

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- With examples, describe and explain the roles that chemistry has in shaping and benefiting society.
- With examples, illustrate how scientific and chemical principles can be applied to help understand and address real-world problems.
- With examples, describe how chemicals can be considered both helpful and harmful.
- Ask an interesting question that chemistry can answer.

To aid in this endeavor, we have introduced the United Nations Sustainable Development Goals (UN SDGs) as an overarching thematic framework for our first-year courses. We have employed a series of active learning modules that promote a systems thinking examination of the Goals and that explore how knowledge in the chemical sciences might aid in achieving them. In this paper, we describe examples of these learning activities, along with the findings of student interviews and surveys to gauge student responses to their use.

■ SYSTEMS THINKING IN CHEMISTRY EDUCATION

This special issue describes aspects of an emerging pedagogical shift toward the use of systems thinking in chemistry education.[15] Systems thinking describes a holistic approach to analyzing how different parts of a system are interlinked and function within the context of that system, which in turn may link to and function within other systems at smaller and larger scales. Introductory general chemistry curricula at the undergraduate level often encompass a multitude of disconnected concepts with seemingly absent connections to everyday life.[15a] A systems thinking approach toward curriculum design seeks to address this concern by complementing traditional reductionist methods in science research and education with inclusion of the application of chemistry concepts and chemical reasoning to multiple scales of real world contexts.[15c]

Although systems thinking reveals that introductory chemistry concepts are necessary to explain and to develop solutions to severe global and anthropogenic crises of the 21st century,[16] those relationships can be obscured by a curriculum heavily focused on factual knowledge.[17] By incorporating a systems thinking perspective into an introductory chemistry curriculum, the relationship of chemistry to real-world contexts and its importance in developing solutions to global-scale environmental and societal issues can be explored. A convenient framework within which to describe such relationships is that of the United Nations Sustainable Development Goals.

■ UN SUSTAINABLE DEVELOPMENT GOALS

In 2015, the United Nations established a framework for the development of a sustainable planetary society in the form of 17 Sustainable Development Goals.[18] These goals promote prosperity and physical and social well-being for all people, while preserving the long-term stability of our climate and ecosystems. Chemistry must play a significant role in the pursuit and achievement of these goals,[19] in that the sustainable conversion of natural materials and energy sources into the food, fuels, materials, textiles, and medicine required by every person are ultimately matters of chemical transformation.[20,21] However, human chemical activity is also a significant driver of many of the problems the UN SDGs are intended to address, and many of the factors that have brought us into the Anthropocene Epoch are chemical in nature.[22,23] As such, the UN SDGs serve to illustrate the tension between the roles of anthropogenic chemical reactions as both a source of and potential solution to the many challenges our society must face in this century. This tension is echoed in a central learning outcome for chemistry education proposed by Holme, "Chemicals have benefits and hazards, and these must be considered together,"[24] a form of which we incorporated into the learning outcomes for our own first-year chemistry courses. As noted by others, this framework can embody the principles of systems thinking,[15b] in that use of the UN SDGs can promote an understanding of chemistry concepts that escapes students when their relevance is traditionally limited to isolated textbook chapters; the UN SDGs instead illustrate the importance of chemistry concepts to multiple interconnected topics that generally lie outside introductory chemistry curricula.

■ LEARNING ACTIVITIES

Beginning on the first day of class and recurring at multiple points throughout the course, the UN SDGs are used as an anchoring framework to which course concepts and topics can be related and as a source of examples through which the broader societal relevance of the course material can be demonstrated. The UN SDGs are visually represented by a set of distinctive and colorful icons, serving as a consistent visual marker that promotes recognition on assignments, presentations, and assessments (Figure 1).[25]

Figure 1. Representative UN Sustainable Development Goal icons. Icons reprinted with permission of the United Nations.[18]

For each of the learning activities described below, these icons were used to draw student attention to specific large-scale societal challenges, into which greater insight and understanding can be gained through an application of chemical principles described in typical first-year chemistry curricula. These learning activities have been designed for use during a typical classroom session in a large lecture hall, with students working together in small (three to four students) groups to develop answers to specific questions and then report those answers to the class as a whole via clickers.

In the final exam for the first-semester and second-semester course of the 2018−2019 academic year, a short open-ended question made explicit reference to the SDGs: "Select one of the [four or five] UN Sustainable Development Goals shown below. Briefly describe how studying chemistry has helped or might help you better understand how our society can achieve this goal." On the second-semester exam, 652 of 656 students

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provided an answer to this question, with an average grade of 79%, indicating that a this framework promoted very high achievement of our corresponding learning objectives.

Shared Document Brainstorm

In the first class meeting in the first term, the UN SDGs were introduced as a thematic framework for the course. The discipline and human activity of chemistry was described to students as being necessary to create the substances required for human society to function. Further, it was pointed out that a truly sustainable society would create its required substances in a manner that consumes only molecules that will always be available and produces no byproducts, innocuous byproducts, or byproducts that can be recycled back to their original starting materials. The class was then divided into prearranged groups of four students, each group was assigned a number from 1 to 17, and the groups were asked to open and complete a shared online document that prompted them to identify ways that chemistry could contribute to the achievement of the SDG corresponding to their assigned number (Figure 2). An attractive feature of such a shared online resource is that the document being edited can be displayed on a class projector screen: in the first classroom session of the course, students can see how their own efforts are creating part of the course content in real time. A summary document that combined group suggestions across three class sections was then made available to students. Near the end of the course in the second term, students were again arranged into four-member groups, assigned an SDG number, and asked to add to the shared summary document the specific course topics or concepts that they saw as relevant to their assigned SDG.


UN Global Goals for Sustainable Development

SUSTAINABLE DEVELOPMENT GOALS

Chemistry is the science of detecting, identifying, analyzing, and making molecules. A sustainable society requires that we *make* all the molecules we will ever need *only* from the molecules we will always have, which is not something we can currently yet achieve.

The 17 UN Global Goals for Sustainable Development are listed below. For your assigned Global Goal, work with your group to identify one way that chemistry can help us achieve it. Write your answer as one of the bullet points beside that Goal.

If your group is satisfied with your answer, or can't think of one, do the same for a Goal with no responses yet, or for a Goal where your group thinks an important idea is missing.

For details about each Global Goal, follow this link or click on each individual graphic.

1 NO POVERTY	• • • •
2 ZERO HUNGER	• • • •
3 GOOD HEALTH AND WELL-BEING	• • • •

Figure 2. Portion of shared online document completed by students. Icons reprinted with permission of the United Nations.[18]

Guided-Inquiry Activities

We use guided-inquiry activities to promote student development of concepts and principles that involve the recognition of patterns and trends and that we believe students can develop on their own with proper direction and scaffolding. In our courses, these concepts include the shapes of atomic orbitals, VSEPR structures, and the physical and structural basis for intermolecular forces and trends in pK_a values. During these activities, groups of students work together in class through cycles of exploration, concept invention, and concept application to construct an understanding of a specific concept,[11] with each student individually reporting their findings to the larger class in the form of responses to accompanying on-screen clicker questions.

For example, one of our guided-inquiry assignments deals with chemical fuels and develops the concept that reaction enthalpies can be interpreted in terms of the bond strengths of reactant and product molecules. The activity incorporates the course topics of thermochemistry, reaction enthalpies, bond strengths, and Hess's Law and applies those concepts to the UN SDGs of (7) Affordable and Clean Energy and (13) Climate Action. (This guided-inquiry activity and its accompanying slides are included as Supporting Information.)

Case Studies

The primary activities we use to apply course concepts to the UN SDGs are short, directed case studies. During each case study activity, groups of students work together in class to discover how multiple concepts recently discussed during different parts of the course can be collectively applied to develop a richer understanding of topics with broader societal relevance. These activities lead students to a systems thinking orientation of a topic by demonstrating that isolated chemistry concepts with application to a single component of a system may be combined to inform a more complete understanding of a problem at a much larger scale. As with the guided-inquiry exercises, small student groups are scaffolded through a series of prompts to identify patterns and answer questions, with each student individually reporting their findings to the class as a whole via clickers. It should be noted that the case study exercises were designed not to develop or directly improve student understanding of course content or concepts but instead serve as detailed examples of their application to relevant systems. That is, these exercises deliberately and exclusively target affective rather than cognitive learning outcomes.

In each case study, links to corresponding UN SDGs are described, indicating how a greater understanding of the subject can aid in the achievement of the Goals. The case study topics were chosen not only for their contextual application of multiple course concepts but also for their relevance to environmental and medicinal concerns not often discussed explicitly in introductory chemistry courses (Figure 3).

For example, midway through the first term of our introductory chemistry sequence, our students have completed course sections on gas laws and kinetic molecular theory, on introductory spectroscopy and the relationship between photon energy and wavelength, on Lewis structures and resonance, and on the correlation of bond order to chemical bond strengths. This allows students to engage in an activity that explores concepts related to anthropogenic ozone depletion, including the relationship between the molecular structures and bond orders in O_2 and O_3 and the UV absorption profiles of these gases, and the role of stratospheric ozone in protecting the Earth's surface from damaging UV radiation. The activity guides students through an analysis of

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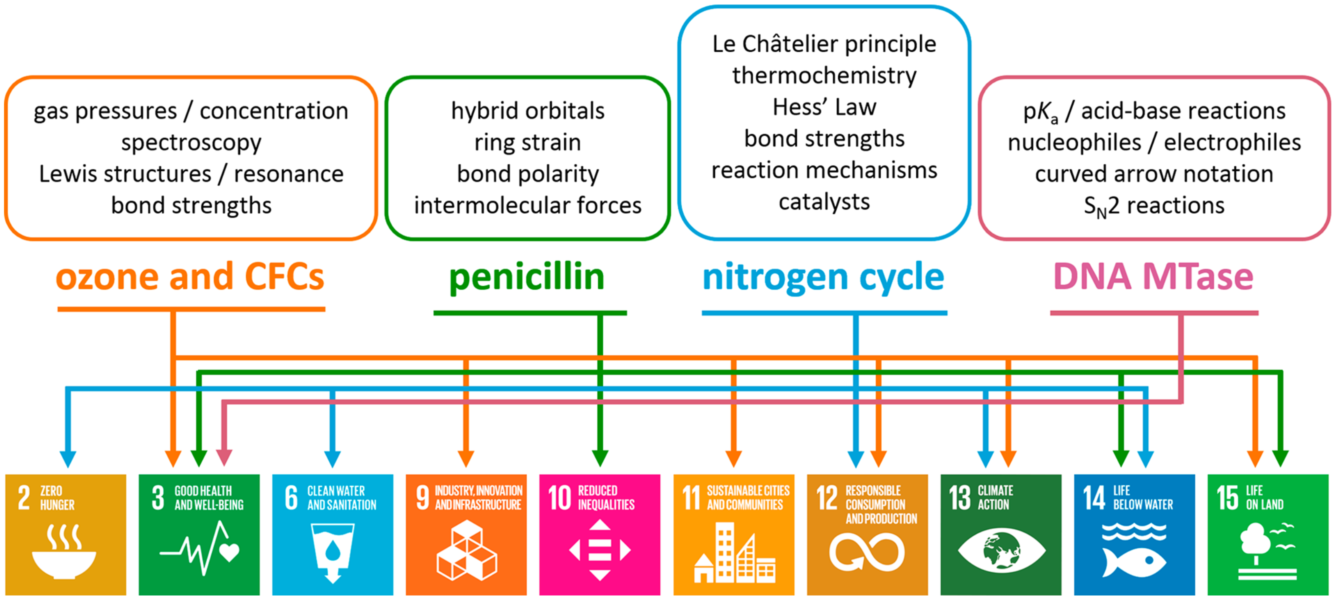

Figure 3. Conceptual map showing the course concepts applied within each case study topic and the links from each case study to relevant UN SDGs. For example, the ozone and CFCs study draws upon course information related to gases, spectroscopy, molecular structure, and chemical bond strengths, and the subject of ozone degradation by CFCs is relevant to SDGs 3, 9, 11, 12, 13, and 15. Icons reprinted with permission of the United Nations.[18]

the chemical and structural bases for the ozone-depleting potentials (ODPs) and global warming potentials (GWP) of different classes of refrigeration gases: chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), hydrofluorocarbons (HFCs), and hydrofluoroolefins (HFOs). The activity describes the historical development of CFCs as nontoxic and nonflammable refrigeration gases, an enormously beneficial technological advancement that resulted in worldwide availability of cheap and reliable refrigeration and air conditioning.[26] When the ability of CFCs to catalytically destroy the ozone layer was first suggested by Molina and Rowland[27] and later confirmed,[28] CFCs were initially replaced by gases with lower ODPs, then by gases with negligible ODPs but high GWPs, and most recently by gases with zero ODPs and negligible GWPs by virtue of their short resident atmospheric lifetimes. These are all properties that can be rationalized in terms of the chemical structures and relative bond strengths of these compounds.[29−31] The activity therefore offers a rich demonstration of Holme's "chemicals have benefits and hazards" central learning outcome, a concept upon which students are asked to reflect at the end of the activity. This case study demonstrates how even relatively simple introductory chemistry concepts permit a sophisticated understanding of an interdisciplinary topic with relevance to multiple UN SDGs: (3) Good Health and Well-Being, (9) Industry, Innovation and Infrastructure, (11) Sustainable Cities and Communities, (12) Responsible Consumption and Production, (13) Climate Action, and (15) Life on Land. (This case study activity and its accompanying slides are available as Supporting Information.)

In a similar fashion, we use other case studies to examine the structure and activity of penicillin; nitrogen cycle disruption by the Haber−Bosch process and the resulting impacts on aquatic ecosystems; and the reaction mechanism of N6a DNA methyltransferase enzymes, which catalyze the transfer of a methyl group from *S*-adenosylmethionine to a DNA adenine amino group via sequential S_N2 and proton transfer reactions.[32] Each study requires the application of concepts from multiple sections of the course and demonstrates the applicability of those concepts to one or more UN SDGs (Figure 3).

■ STUDENT RESPONSES

Research Questions

Our principal goals in introducing the SDG framework to our introductory chemistry courses were to promote an increase in student engagement and interest in the course material and to support achievement of the affective learning outcomes that formed part of the impetus for our course redesign process. However, in the case study exercises in particular, the application of course concepts to the broader contexts represented by the SDGs required recall and consideration of those concepts, so we were also interested in learning to what extent students felt that these exercises were helping them to learn those course concepts. As part of an ongoing larger study to assess the impacts and success of this redesign, we have undertaken both student surveys and semistructured student interviews to address the following research questions about the use of the SDG framework:

(1) What are the student reactions to and satisfaction with the SDG-framed learning activities?

(2) Does the SDG framework help to demonstrate the relevance of chemistry to student experiences?

(3) To what extent do students believe the SDG-framed case study activities help them to learn and understand course concepts?

Research Methods and Participants

The above research questions were investigated using a mixed methods approach: both qualitative and quantitative analyses were performed. Quantitative survey data offered large-scale feedback regarding the effectiveness of the SDG-framed case studies and other active learning activities; 357 students (55%

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of the 649 students registered in all course sections) allowed their survey feedback to be included in this study. Participants ($N = 7$) were recruited for qualitative semistructured interviews that allowed for richer, more in-depth data concerning student satisfaction with the case study exercises.

Survey and Interview Results

At the end of the academic year, all students were asked to complete an anonymous online survey to gauge the extent to which students believed the various active learning activities helped them to learn the course material. The survey comprised five 7 point Likert scale questions asking students to "Rate how you believe [a particular set of course activities] has helped you to understand and apply the concepts in this course," with a rating of 1 designated as, "I do not find this activity to be at all helpful," and 7 designated as, "I find this activity to be extremely helpful." The survey shows that a smaller proportion of students found the case study exercises to be helpful in developing their understanding of course concepts, as compared with the other active learning activities in the course (Figure 4). This is unsurprising, in that the case

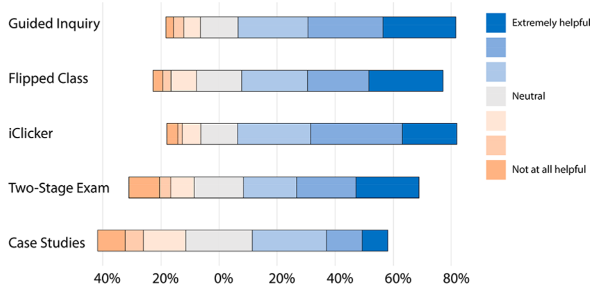

Figure 4. Diverging stacked bar chart of student responses ($N = 357$) to the prompt "Rate how you believe [the specified set of activities] helped you to understand and apply the concepts in this course." The positive (blue) responses regarding the SDG-linked case studies compose 47% of the total.

study exercises did not introduce or develop any new course concepts and were not designed explicitly with the goal of supporting cognitive learning gains. Even so, 47% of respondents perceived the case study activities to support their learning of the relevant course content, with 30% believing otherwise and 22% responding neutrally to that statement. This suggests that the SDG-linked case study exercises had a positive impact on cognitive learning for a large number of students.

A small number of students were invited to participate in semistructured interviews, in order to assess student satisfaction with the case study activities. These initial interviews were intended to be exploratory, to explore the strengths and weaknesses of the activity format and to identify aspects for improvement and subsequent assessment in a larger, more robust study. The interviews provided participants with three prompts:

(1) Were there any specific aspects of the case study exercises that you thought were especially effective?
(2) Were there any specific aspects of the case study exercises that you thought could be improved?
(3) Do you think that the subject of chemistry has any relation to what you experience in the real world?

Overall reactions in these exploratory interviews reveal widespread agreement among participants that the relationships and interconnectivity among chemical concepts, as well as their links to real-world contexts, were clearly portrayed through these case studies and that such connections helped students to learn those concepts. The responses also demonstrate elements of systems thinking among participants: participants described an appreciation that chemistry concepts and chemical reasoning are relevant to problems beyond the confines of a traditional first-year chemistry curriculum and beyond the mere molecular scale. Example comments include:

> *If you don't appreciate what you're learning, you're not going to care about learning it and it won't stick in your brain. It's one of the major problems I have with this course is that there is a massive disconnect.*
>
> *I think it's easy to think of chemistry as just particles and just a theory you have to memorize, but it's really everywhere.*
>
> *It was really interesting to put the chemistry into real terms.*
>
> *It makes me more interested. I'm somebody who, if I'm going to do a course, is like 'so what?'*

However, some students also felt that there was room for improvement in the delivery of the case studies related to the time allotted for the activities and a need for a more well-developed scaffolding of concepts. For example, one student suggested:

> *It was too condensed. It needs to be a little more methodically step by step.*

To address these concerns, future iterations of the activity will provide more background to the explored problem, possibly as readings, videos, or other media assigned prior to class, to better set the stage of what will be tackled in the next class. This will serve to clarify the purpose of each case study, add some general context to create greater appreciation for the topic, refresh the students on previously learned concepts, and allow more in-class time devoted to developing and applying concepts. In addition to the constructive feedback, students recognized the importance of the activity.

■ CONCLUSION

We have employed the United Nations Sustainable Development Goals as a thematic framework in introductory chemistry courses. Using a systems thinking perspective, the SDGs are explicitly linked to course content using active learning activities that demonstrate the applicability of introductory chemistry concepts to challenges associated with various societal, environmental, and global challenges. In particular, we have developed targeted case studies that apply concepts from groups of course topics within a single framing system that links to multiple SDGs. Although students have expressed concerns regarding the pace and conceptual scaffolding of these activities, student interviews and surveys reveal an overall agreement that this SDG framework has been effective in promoting affective learning with regard to the relevance and societal importance of chemistry and in helping maintain student interest and engagement. In addition, many students believe these SDG-linked activities aid their learning of course concepts.

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ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.9b00307.

- Sample guided-inquiry assignment (chemical fuels) (PDF)
- Sample guided-inquiry assignment clicker slides (chemical fuels) (PDF)
- Sample case study activity (ozone and CFCs) (PDF)
- Sample case study activity clicker slides (ozone and CFCs) (PDF)

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Notes

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.

The authors declare no competing financial interest.

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