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The End of Simple Problems: Repositioning Chemistry in Higher Education and Society Using a Systems Thinking Approach and the United Nations' Sustainable Development Goals as a Framework

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ABSTRACT: The purpose of this paper is to discuss ways that a chemistry course could reposition itself by adopting interdisciplinary approaches based on systems thinking and the Sustainable Development Goals (SDGs) as overarching frameworks, to give an overview of several challenges that chemistry in higher education is facing, and to discuss how those can be addressed as a result of this repositioning. We will be discussing the need for a new type of scientist, one who has a deep understanding of their own discipline but also an overview of the links with other disciplines and is equipped with skills that will help them contribute to the solutions of a very complex system: the human−environment interaction system. Chemists should be part of what is described by earth systems' science as "the new social contract" between science and society. Finally, we will explore how this can be reflected in the curricula of higher education, and we will present a University of Bristol educational initiative, Bristol Futures, that attempts to address this.

Problem type	
"Classical" problems	Modern challenges reflecting sustainable development goals (SDGs)
Specialized experience • Strong disciplinary approach	Holistic experience • Interdisciplinary • Multidisciplinary • Cross disciplinary
Less aligned with environmental and societal challenges	Well aligned with environmental and societal challenges
Commonly reflected in higher education curricula	Usually not reflected in higher education curricula

Rationale	
Query	Answer
What is the role of science and chemistry in meeting environmental and societal challenges?	Increasing knowledge and understanding, bettering our lives, solving challenges, and addressing social needs
What kind of science and chemistry can do this?	Depends on the problem, challenge, question, or need

KEYWORDS: *Systems Thinking, Sustainability, First-Year Undergraduate/General, Second-Year Undergraduate, Interdisciplinary/Multidisciplinary, Collaborative/Cooperative Learning, Computer-Based Learning, Distance Learning/Self Instruction, Internet/Web-Based Learning, Student-Centered Learning*

It is widely accepted by many scholars that it was the launch of Sputnik in 1957 that spurred the need to reform higher education and particularly education related to STEM sciences.[1,2] Subsequently, the birth of chemistry education[2] occurred, which in September 2013 celebrated its 50th anniversary. During these 50 years, much has changed; technological advances and the use of the Internet and computers has contributed to significant changes in the way we perceive the world. Unsurprisingly, this has affected not only the ways we perceive and deliver educational material in higher education but also the ways we can teach and assess that material. Emerging pedagogies now include technologically enhanced learning, online learning, virtual realities, blended learning, and asynchronous learning. Although chemistry education has taken some steps toward incorporating many of these pedagogies in higher education curricula, there are still significant and important steps that need to be taken for chemistry to achieve perhaps the most important goal it has to achieve in the 21st century: to remain socially relevant, by which we mean that it must be perceived as being part of the solution of modern global and local challenges, and this needs to be reflected in higher education curricula.

We theorize that in order for chemistry and chemistry education to remain socially relevant, it needs to not only incorporate these new pedagogies into the various curricula but also align itself with three main themes: systems thinking, sustainable development and the Sustainable Development Goals (SDGs), and interdisciplinary work.

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In their 2006 literature review "Factors affecting Curriculum Development in Chemistry", Mbajiorgu and Reid[3] present evidence from their research that can be summarized under four headings: (a) "Chemistry for whom?", (b) "What chemistry?", (c) "How to be taught?", and (d) "How to be assessed?" We will be using these four headings as starting points, and throughout this paper, we will offer our thoughts on what some of the answers might be.

Two critical points are made in the same report by Mbajiorgu and Reid.[3] The first relates to problem-based learning, which we will be discussing from the point of view of "problem-based thinking". The second relates to the fact that only a very small number of chemists actually become bench chemists, and, the report continues, it is critical that chemistry education moves away from "simply producing lab chemists".

We will discuss that it is perhaps time for chemistry, as has been the case with other STEM disciplines, to aim toward producing graduates that have both a deep understanding of chemical phenomena as well as an appreciation of how chemistry relates to other disciplines. This should encompass global and local challenges with an emphasis on how the discipline can critically contribute to addressing these challenges. We will also present a University of Bristol educational initiative that we believe can enhance the experience of undergraduate chemists by adding the much-needed interdisciplinary approach, systems thinking, and sustainable development in the curriculum.

■ SYSTEMS THINKING

The term "systems thinking" is attributed to Barry Richmond (1987), and since then, the term has been defined and redefined.[4,5] For the purpose of this paper, we will be borrowing parts of Senge's definition as well as Sweeney and Sterman's definition,[6,7] and we will define systems thinking as "a holistic approach that enables simultaneous analysis of the parts as well as the whole itself, their evolution, overlaps, and dynamic interactions". Using this definition, it is very useful to first examine chemistry as part of a larger system, before we examine it in higher education in isolation. The role of chemistry within higher education cannot be discussed separately from the role of chemistry within science, which in turn cannot be discussed separately from the role of science in relation to society.

Science for Whom?

As early as 1938, J. D. Bernal published an essay on *The Social Function of Science*[8] where he discussed the role of science as both an outcome of social forces but also as a social force itself:

> *Science, conscious of its purpose, can in the long run become a major force in social change. Because of the powers which it holds in reserve, it can ultimately dominate the other forces. But science unaware of its social significance becomes a helpless tool in the hands of forces driving it away from the directions of social advance, and, in the process, destroying its very essence, the spirit of free inquiry.*

According to Bernal, science, in addition to contributing to our understanding of the natural world, has a social role to play, which in essence is applying this knowledge in order to make our lives better. The demand for greater "social relevance" of science and academic programs reappears frequently in the literature.[9−14] As discussed in detail in the 2004 Dalhem Workshop Reports "Earth System Analysis for Sustainability",[15] it is possible that we all together need a new "social contract between science and society". It becomes clear that the answer to the question "what is the purpose of science" and the answer to the question "science for whom" both have the same answer, which is "society".

What Science?

Answering these questions unavoidably raises the question of "which science" or "what kind of science" is equipped to achieve these goals. Over the last few centuries, different disciplines have generally evolved in isolation from each other to the extent that we now speak of overspecialization in some areas.[16] From C. P. Snow's introduction of the "two cultures" theory in 1959 and Kuhn's suggestion in 1962 that devotion to a scientific paradigm can prevent absorption of new facts and knowledge to the work of MacKinnon, Hine, and Barnard in 2013, there are ample critiques in the literature that no one science alone is equipped enough to solve every challenge we are facing.[17−19] The societal demand for greater "relevance" of science and academic programs appears in the 1974 paper by Swora and Morrison "Interdisciplinarity and higher education",[9] whereas in 2013 MacKinnon, Hine, and Barnard reach an excellent conclusion where they describe interdisciplinary work not as a means to an end but as a natural progression in the scientists' quest to answer a question and solve a problem:[19]

> *The movement toward the interdisciplinary mode facilitates this restructuring in that disciplines are not demolished but are made to focus on their relationships with one another and with the problems of society.*

Additionally, as described in "Interdisciplinary science research and education":[19]

> *For the scientists in our vignettes (case studies), interdisciplinarity was a natural progression in their scientific quest. They did not set out to engage in interdisciplinary science, rather they focused on solving a problem.*

Earth systems science and the science of sustainability or sustainable development are directly and indirectly trying to answer the question of "which science" by introducing methods, approaches, and frameworks that are deeply interdisciplinary, and they use systems thinking in order to examine, as we defined, both the parts and the whole of the system. So far, we have presented some key interactions in the system we are attempting to describe. Science (apart from advancing our knowledge and understanding) needs to address societal needs and problems, and in its effort to do this, it needs to be flexible enough to adopt either strong discipline-focused practices or strong interdisciplinary practices.

■ GLOBAL CHALLENGES

The point highlighted in the extract from MacKinnon, Hine, and Barnard[19] is very important: it is the problem (challenge or question) the scientist is trying to address that will define the appropriate approach or the appropriate kind of science. This leads us to the next question: What are the current problems or, as we call them, global challenges? We now live in the era of the Anthropocene,[20] where humans are a globally significant force capable of reshaping the face of the planet. In the case of the human−environment interaction system, the myriad ways that humans have been changing the planet are a side-effect of our "learning about global change by doing global change".[21] In 2015, the United Nations (UN), moving from their Millennium Goals, introduced their 17 Sustainable

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Development Goals (SDGs)[22,23] (Box 1), a framework whose purpose is to map the challenges humanity must solve in order to keep living on this planet. Each goal addresses one global challenge, but every goal has several targets that need to be addressed. In total, the 17 SDGs have 169 targets. These goals and targets were agreed upon by 193 member states.

Box 1. Sustainable Development Goals (SDGs)

1. End poverty in all its forms everywhere.
2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture.
3. Ensure healthy lives and promote well-being for all at all ages.
4. Ensure inclusive and quality education for all and promote lifelong learning.
5. Achieve gender equality and empower all women and girls.
6. Ensure access to water and sanitation for all.
7. Ensure access to affordable, reliable, sustainable and modern energy for all.
8. Promote inclusive and sustainable economic growth, employment and decent work for all.
9. Build resilient infrastructure, promote sustainable industrialization and foster innovation.
10. Reduce inequality within and among countries.
11. Make cities inclusive, safe, resilient and sustainable.
12. Ensure sustainable consumption and production patterns.
13. Take urgent action to combat climate change and its impacts.
14. Conserve and sustainably use the oceans, seas and marine resources.
15. Sustainably manage forests, combat desertification, halt and reverse land degradation, halt biodiversity loss.
16. Promote just, peaceful and inclusive societies.
17. Revitalize the global partnership for sustainable development.

We humans decided that these are currently the most pressing issues for our future and survival. Unlike the problems and challenges we faced 20 years ago or even 10 years ago, it is becoming increasingly obvious that the human−environment interaction system is potentially more complex than we thought, making the challenges we are facing more complex and implying that the solutions needed to address these challenges are also likely to be complex. There are no simple, single solutions to climate change, much like there are no simple solutions to poverty; we are potentially witnessing the end of simple problems in science. It is critical that this realization is not only reflected in higher education curricula but, in the case of chemistry education, is reflected explicitly in the core content, learning outcomes, and skills the graduate needs to develop.

CHEMISTRY AND CURRICULA

Chemistry has been defined as "a science that deals with the composition, structure, and properties of substances and with the transformations that they undergo". This definition, reflected in the structure and content of several higher education curricula, begs one very simple question: in the era of the Anthropocene, the age of technology, the internet, and information, is this all chemistry has to offer? Although the answer to this question is "of course not", this is not explicitly reflected in several higher education curricula. In their "Report of a Literature Review" in 2006, Mbajiorgu and Reid[3] state:

> *When faced with the question, 'what chemistry?', the temptation is to list the topics and themes to be included in a syllabus. These are usually defined by the logic of the subject as well as the needs of later stages of learning. This approach must be resisted... There needs to be a massive paradigm shift in thinking and the willingness to jettison much traditional chemistry.*

An excellent alternative is described in the work of Matlin and co-workers and Mahaffy and co-workers,[14,24−26] where the links of chemistry in a sustainable future are described, followed by introductions to "one world chemistry" and eventually calls for the reorientation of chemistry through systems thinking. This approach to chemistry and chemistry education reflects a large part of the educational initiatives we will be describing; this "new chemistry" has a very important role to play in most of the global challenges, and it is uniquely placed to play a leading role in addressing several of the SDGs. In Table 1, we present those SDGs that have a direct link with chemistry and the chemical sciences and those SDGs that would be indirectly influenced by the advancement of the former. We base this classification on the UN's targets and indicators related to each SDG.

Curriculum change or curriculum reform has never been an easy task, nor are we implying that it can be done without a lot of resources spent or invested energy and time that academics often do not have.[27−30] However, aligning the curriculum with systems thinking, interdisciplinary thought, and the framework provided by the SDGs we believe can transform the content provided to undergraduate students, and the simultaneous use of new and exciting pedagogical approaches, such as online, blended, and asynchronous learning, can help with both timetabling and workload concerns. Below we present two parts of the same educational initiative that we believe can offer just that, and we provide a map of how we believe this initiative can enhance the student experience of the undergraduate chemist.

UNIVERSITY OF BRISTOL EDUCATIONAL INITIATIVE: BRISTOL FUTURES

In 2005, the United Nations (UN) General Assembly declared a Decade of Education for Sustainable Development (DESD, 2005−2014) and invited all educational institutions to contribute to education for sustainability.[31−33] The University of Bristol is a member of the Global Action Programme (GAP) and is a Sustainable Development Goals (SDG) Accord partner institution.[31,33−35] In response to these initiatives, it has developed Bristol Futures, a creative and integrated approach to curriculum development that aims to develop student skills and values in sustainable futures, global citizenship, and innovation and enterprise.[33,35−40] Bristol Futures is one of the University of Bristol's strategic projects that seeks to equip all students with the skills needed to be informed, engaged citizens and scientists in a changing world and will be completed in three phases. Additionally, the University of Bristol has developed a skills framework, the Bristol Skills Framework.[33,41,42]

Bristol Futures is not an initiative targeting chemistry students only, but because it is offered across the University, it gives undergraduate chemists the possibility to (a) interact with global and local challenges; (b) explore the relevance of

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Table 1. Sustainable Development Goals, Categorized by Whether Chemistry Can Play a Direct, Leading Role or an Indirect, Assistive Role in Addressing Them

Sustainable Development Goals (SDGs)[22,23]	SDGs for Which Chemistry Can Play a Role, Addressing Specific Targets and Indicators	
	In a Leading Role	In a Helping Role
1. End poverty in all its forms everywhere.		Indirectly
2. End hunger, achieve food security and improved nutrition, and promote sustainable agriculture.	Directly	
3. Ensure healthy lives and promote well-being for all at all ages.	Directly	
4. Ensure inclusive and quality education for all and promote lifelong learning.		Indirectly
5. Achieve gender equality and empower all women and girls.		Indirectly
6. Ensure access to water and sanitation for all.	Directly	
7. Ensure access to affordable, reliable, sustainable, and modern energy for all.	Directly	
8. Promote inclusive and sustainable economic growth, employment, and decent work for all.		Indirectly
9. Build resilient infrastructure, promote sustainable industrialization, and foster innovation.	Directly	
10. Reduce inequality within and among countries.		Indirectly
11. Make cities inclusive, safe, resilient, and sustainable.	Directly	
12. Ensure sustainable consumption and production patterns.	Directly	
13. Take urgent action to combat climate change and its impacts.	Directly	
14. Conserve and sustainably use the oceans, seas, and marine resources.	Directly	
15. Sustainably manage forests, combat desertification, halt and reverse land degradation, and halt biodiversity loss.	Directly	
16. Promote just, peaceful, and inclusive societies.		Indirectly
17. Revitalize the global partnership for sustainable development.		Indirectly

their degree to these challenges; (c) interact with young scientists from other disciplines; and (d) explore their discipline and degree in relation to other disciplines, degrees, and approaches.

The core of Bristol Futures is formed by three "pathways", defined as

- Sustainable Futures (SF): equipping students to engage with the challenges of globally improving the quality of life for humanity while sustaining the natural environment and finding ways of living with the environmental change that we cause.[33]
- Global Citizenship (GC): fostering the critical self-reflection and understanding students need to negotiate the challenges of energy and resource management and food security, tackle international insecurity, and engage with culture and heritage in an increasingly globalized world.[33]
- Innovation and Enterprise (IE): enabling students to act on their ideas, use their initiative, and shape change in diverse sectors.[33]

In this work we will only be discussing the Sustainable Futures pathway.

SUSTAINABLE FUTURES ONLINE OPEN COURSE

The first phase of this educational initiative is the Sustainable Futures massive online open course (MOOC).[33,43,44] This is a noncredit bearing course open to everyone; however, University of Bristol students are offered additional incentives in order to join and successfully complete it.

SFOC Development and Delivery

The main goal of the Sustainable Futures Online Course (SFOC) is to take sustainability beyond its obvious and most frequently used links, to connect sustainable development to challenges like homelessness and resilient cities, personal happiness and well-being, and a sense of purpose in life.[33,45−48] It introduces learners to interdisciplinary challenges related to several sustainable development goals as well as the three pillars of sustainability (environment, economy, and society).[32,33,49,50] For the SFOC, access is not restricted to University of Bristol students or even just students. Therefore, in this case, we are discussing the "learner" instead of the student. This course was designed by a core interdisciplinary team and an extended team of online and e-learning experts and is delivered online, through the platform FutureLearn.[51] This course was fully codeveloped by (a) a large, interdisciplinary group of academic members of staff; (b) students; (c) a large team of external partners; and (d) industrial partners. Codevelopment of the course, particularly in collaboration with students, ensured that delivery of the course would address student concerns (e.g., those related to timetabling and workload); particular consideration was given to making explicit and direct links throughout the course to different disciplines, as well as using language and context that would be accessible and understood by both social and natural science students. Access to this course is free of charge and it runs over 4 weeks, with 3 h of interactive and self-directed content per week, requiring a total of 12 h of commitment from the learner; no previous in-depth understanding of such challenges is expected.[33]

Three main overarching themes are used across the course: sustainable development, systems thinking, and interdisciplinarity. Learners are given the chance to explore several themes in the form of case studies of individuals and organizations that engage in some way with the SDGs and the challenges we are presenting: personal and professional well-being and purpose, food and food waste, energy and energy use, homelessness, climate change and greenhouse gases, plastics and microplastics, sustainable development abroad (Albania), personal challenges, and mental health. We adopted three different scales of examining modern challenges through the lens of the SDGs: from the personal to the local (Bristol), from the local to the global, and from the global back to the personal. These case studies were used as a tool for the students to engage with more than just the theory and develop a deeper understanding of the complexity of the interactions in the human−environment system. It provides the students with role models and real situations that they can relate to, thereby enhancing their deep, long-term learning. By engaging with these case studies, learners engage with several experts, all representing different aspects of either the challenge or the solution. This gave us the opportunity to explore research-led teaching in an online environment.[52−56]

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Table 2a. Overview of the Content Presented in Week 2 of SFOC in Relation to the SDGs Presented in This Week of the Course and the Relevance[a] to Chemistry Education Regarding the Content and Skills Developed

Week 2	Introduction to Week 2	Food	Energy	Homelessness
Course Content	The roles we take	Case study: The origins of Fareshare	Introduction to energy	Introduction to homelessness
	An introduction to the themes and case studies	Case study: Just eat it	Case study: Geneco	Case study: Saint Mungo's
	Introduction to food	Case study: FoodCycle	Case study: The energy efficient home	Case study: Understanding homelessness
		Food: What do you think?	Case study: Smart energy management at the University of Bristol	Case study: Political initiatives to support the homeless
SDGs	1. No poverty			
	2. Zero hunger			
	3. Good health and well-being			
	4. Quality education			
	5. Gender equality			
	7. Affordable and clean energy			
	9. Industry innovation and infrastructure			
	10. Reduced inequalities			
	11. Sustainable cities and communities			
	12. Responsible consumption and production			
		Relevance to Chemistry Education		
Content	L	M	H	L
Skills	M	M	H	M

[a]Low (L), medium (M), or high (H).

Finally, discussion points throughout the course give the learner the opportunity to engage as an active contributor in a dialogue between the learner and the academic.[57] The discussion points facilitate interactions among the learners, which has several benefits, such as (a) developing interactions and consistency among the cohorts, (b) facilitating social learning and sharing, (c) allowing the learner to explore different aspects of the case studies,[33,58,59] and (d) promoting overall deep learning[60,61] through social learning as the amount of content that could be explicitly delivered online was limited. Learners are given information on how to join local initiatives and ways to contribute and interact, as well as spaces and events where they can engage with others.[46,59,62] Additionally and in order to give the learner a sense of the bigger picture, there are also challenges not strictly local to Bristol. This showcases the scale of modern global challenges and the need for collective action beyond the University and the city.

SFOC Assessment and Feedback

We provide feedback in two ways: (a) participation in the discussions and (b) providing weekly videos. In the discussions, we comment in writing and answer questions that are either content specific or contextual. Then at the end of every week, we provide feedback in the form of a video; after going through every week's comments, we address the most important questions on video, reward the students that were very engaged by pointing out how much they helped their cohort and thanking them for their participation, which also encourages the ones that are not commenting and participating in the discussions to do so. The benefits of filmed feedback are that the students feel there is an interaction with the lead educators (i.e., they can see that the core teaching team has read and interacted with their comments), and it promotes further interaction with the discussions in the course. The responses we have gotten from the video feedback have been extremely positive. Overall, the learners are assessed through the percentage of the course they have completed. In this specific course, we have not added additional assessments through online quizzes. For the assessment, we are not using online quizzes, and the only form of assessment is the completion rate of the course as defined by FutureLearn guidelines (successful completion of 80% of the course).

SFOC Benefits Specific to Chemistry and Chemistry Education

We believe that overall, the undergraduate chemistry curriculum should explicitly and specifically include those sustainable development goals that chemistry and chemical sciences could and do have a direct impact on (Table 2a). Furthermore, we strongly believe that the interdisciplinary nature of the case studies presented in the SFOC can provide these links between chemistry and the SDGs, as we discuss below.

There are five key points we believe this online course can help improve within the undergraduate chemistry curriculum:

1. The student interacts with several of the SDGs and explores links specific to chemistry through the case studies and the filmed feedback.
2. This course offers research-led teaching in an online environment, giving the student the flexibility to control the time and duration of their learning.
3. The students engage with interdisciplinary, international, transgenerational cohorts, thereby gaining not only the different perspectives of other disciplines but the experiences of different age groups and different cultures.
4. Each case study is presented by several different experts who discuss not only the challenge from their expert viewpoints but also how they got to where they are in their lives and careers.
5. The skills an undergraduate chemist can develop during this course are creativity, intellectual abilities, self-management, personal well-being, personal effectiveness, engagement, and communication.

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Table 2b. Overview of the Content Presented in Week 3 of SFOC in Relation to the SDGs Presented in This Week of the Course and the Relevance[a] to Chemistry Education Regarding the Content and Skills Developed

Week 3	Introduction to Week 3	Microplastics	Greenhouse Gases, Industry, and Climate Change	Sustainable Development in Albania
Course Content	Change mechanisms and roles for Global Change	Introduction to microplastics	Introduction to greenhouse gases, industry, and climate change	The situation in Albania and how it links to sustainability
	An introduction to the themes and case studies in week 3	Case study: Understanding microplastics	Understanding CF_4 emissions	Case study: Sustainable development in Albania
		Case study: CodSteaks	Case study: Edwards	Sustainable Development Goals in Albania
		Case study: Ellen MacArthur Foundation	What roles have people played?	
		Can you avoid using plastic?		
SDGs	6. Clean water and sanitation			
	9. Industry innovation and infrastructure			
	11. Sustainable cities and communities			
	12. Responsible consumption and production			
	13. Climate action			
	14. Conservation and sustainable use of the oceans, seas, and marine resources			
	Relevance to Chemistry Education			
Content	M	H	H	L
Skills	M	H	H	H

[a]Low (L), medium (M), or high (H).

Tables 2a and 2b summarize the content delivered in weeks 2 and 3 of the course, mapped against the SDGs discussed in those weeks and the relevance to the chemistry undergraduate curriculum. We have assigned a high (H), medium (M), and low (L) values to describe the relevance of the content presented within SFOC in relation to education of the "new chemistry" discussed above (as well as the "One world Chemistry" as defined by Matlin[14]), and we use the same values to describe the skills that can be developed that are relevant to the needs of undergraduate chemists. In this work, we define the skills presented in the Bristol Skills Framework.

Table 2a presents a brief overview of the content presented in week two of the SFOC in relation to the SDGs discussed either directly or indirectly. We assigned a value of medium for both the skills and content for the case study of food and food waste as this case study was designed to focus on several bottom-up, student-led initiatives regarding food and food waste instead of an "academic" or "expert" approach. This case study was designed to work as an introduction to numbers and facts related to food and food waste, invite the learner to think critically and discuss with others, and most importantly present to the learner what students are doing to address this issue. Regarding energy consumption and production, we assigned a value of high for both the skills and content as this case study discussed in depth the chemistry behind the technologies presented and presented research and career opportunities more suitable for an undergraduate chemist. Finally, in the case study of homelessness, we assigned a value of low for content relevance as this case study was not directly linked to chemistry or chemical sciences. However, we assigned a value of medium for the skills as this section discussed different career paths for different people, which could give perspective to the undergraduate chemist and help them reflect on the skills acquired during their degree and future career pathways.

Table 2b presents a brief overview of the content presented in week three of the SFOC in relation to the SDGs discussed either directly or indirectly. For the case study of microplastics, we assigned a value of high for both the content and skills in relation to the relevance to chemistry and chemical sciences because for this case study, we presented expert work done by academics at the University of Bristol involving the challenge of microplastics along with the science and field work behind this challenge. For the case study of greenhouse gases, we assigned a value of high for both the content and skills as we presented the challenge of climate change from an atmospheric chemistry and industrial point of view. Finally, for the case study related to sustainable development in Albania, we assigned a low value for the content but a high one for the skills as this case study examined scales and time scales of change, stakeholders, and different approaches to solving a problem.

■ SUSTAINABLE DEVELOPMENT OPTIONAL UNIT

The second phase of the Bristol Futures educational initiative is the introduction of an optional, 20 credit point unit offered to students across the University of Bristol who have suitable optionality within their degree programs. The Sustainable Development Optional Unit (SDOU) was built using the same overarching themes: sustainable development, systems thinking, and interdisciplinarity. The unit is currently completing its first run (teaching block 2, 2019) and has been selected as an optional unit by more than 250 students across most faculties and disciplines of the University.

SDOU Development and Delivery

For this unit we are using a blended learning approach that consists of (a) online delivery of the core learning materials, presented in the form of briefs and blog-like articles, and (b) six 2 h compulsory workshops of approximately 50 students each where the students interact with the core team and the extended teaching team (consisting of 6 teaching assistants).

The unit is structured in the form of six blocks of different content: introduction to sustainable development; science and understanding; behavior and organizational change; economy, policy, and law; equality and justice; and technology and innovation. The different content areas were designed to align with the majority of disciplines and schools within the university of Bristol and guide the students through early

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concepts of sustainability and simple systems to more elaborate thinking, frameworks, and complex systems. Overall, the purpose of this unit is to explore the links of different disciplines to sustainable development, emphasize the need of systems thinking in order to address global challenges, and introduce interdisciplinary work early in undergraduate studies. This unit focuses on developing skills more than retention and repetition of information taught; during the 2 h workshops, the students must engage in different activities that require them to develop their critical and analytical thinking skills and negotiating skills, lead a team and be part of a team, present, and research.

SDOU Assessment and Feedback

This unit is a pass−fail unit, and the students are assessed on the basis of a portfolio they must produce. The students are required to pass all assessments in order to pass the unit. The portfolio consists of a group project, online contributions, and reflective writing.

Group Project (Wiki Project). A central part of the Sustainable Development unit is the production of a wiki, which accounts for 40% of the assessment. Working in groups, students choose one of four case studies to cover in their wiki project and are assigned to a group that includes people from other disciplines. They conduct guided research on the chosen case study during the second hour of the workshop. In their group, they create a wiki that provides a briefing on a specific case study for a given Sustainable Development challenge. The briefing should be directed at an identified audience (e.g., a city authority, a company executive, a government department, a community organization, an international campaigning NGO, etc.). The challenges offered in the case studies are fairly wide-ranging. Students may choose to focus on evaluating the role of a particular technological innovation, the impact of alternate water provision policies on poor and marginalized members of a community, or potential behavior change strategies to encourage people to eat less meat. The wiki exercise is designed to encourage students to think about how sustainable development involves the interplay (sometimes harmonious, sometimes not) of different components derived from different academic backgrounds.

This sort of group learning activity may be new to students in two ways: (a) The first is active learning as a group activity: Being able to work in interdisciplinary teams is an essential skill in any future career but is particularly important to sustainable development. (b) The second is writing for the web: We get lots of practice at reading electronic resources. Here, students get a chance to think about the creation of web resources. How do we show authority when writing for the web? What are the particular challenges of writing brief but accurate web pages? How do we link ideas together differently when working electronically?

Online Contribution and Reflective Writing. The students are expected to participate in online monitored discussions where they are required to both start a discussion themselves but also comment on discussions started by others. Additionally, they are expected to produce reflective pieces of approximately 300 words. This accounts for 60% of their assessment.

Overall, the online and offline activities that generate content for the portfolio, together with the final reflective writing piece, are intended to

- Develop their ability to creatively apply ideas and concepts drawn from a number of disciplines to specific Sustainable Development challenges and scenarios.
- Engage with others (both online and face-to-face) in constructive debate and critical discussion regarding Sustainable Development challenges and potential ways forward.
- Reflect on the application of the ideas and concepts learnt in the unit to challenges facing those trained in their own disciplines, either within academia or in professional careers beyond, and therefore how they may impact their own futures.

SDOU Benefits Specific to Chemistry and Chemistry Education

Overall there are five key points we believe this online course can help improve within the undergraduate chemistry curriculum:

1. It allows the student to interact with deeply interdisciplinary content in a blended learning environment and explore links specific to chemistry.
2. Systems thinking and sustainable development are embedded in the online and offline content as well as in the personal and professional practices of the core and extended teaching team, offering the students an excellent environment to engage with these concepts and ideas.
3. It helps the student develop critical and analytical thinking regarding global challenges while exploring solutions for these challenges as part of a larger interdisciplinary team.
4. It allows the students to develop critical skills: knowledge, creativity, intellectual abilities, self-management, personal well-being, personal effectiveness, engagement, teamwork, and communication.
5. It advances the students' personal and professional development.

Table 3 summarizes the content delivered in every block of the course, mapped against skills developed as part of the workshops' activities and relevance to the chemistry undergraduate curriculum.

The SDOU online content was designed to take the student (in this case, the undergraduate chemist) on a journey: Block 1 introduces basic concepts, frameworks, and ideas; Block 2 discusses science and our understanding of the world while introducing qualitative and quantitative methods and approaches; Block 3 introduces the student to behavior and organizational change; Block 4 addresses issues related to law, equality, and policy; Block 5 addresses issues of equality, justice, and racism; and finally, Block 6 discusses technology and innovation. In every block, the undergraduate chemist has the opportunity to identify how chemistry fits into the content discussed under the specific block, reflect on this and discuss it online with their cohort. Additionally, the workshops and the intensive activities give the undergraduate chemist the opportunity to actively work on developing their skills and their personal and professional development in a safe environment moderated by a team of expert teachers.

■ EVALUATION OF THE SFOC AND SDOU

The SFOC has now completed its fourth run. To evaluate the impact of the course, we are collecting metrics related to the

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Table 3. Overview of the Online Content Presented the Sustainable Development Optional Unit in Relation to the Offline Content (Workshop Activity) and the Relevance[a] to Chemistry Education Regarding the Content and Skills Developed

Block 1: Introduction to Sustainable Development	Block 2: Science and Understanding	Block 3: Behavior and Organization Change	Block 4: Economy, Policy, and Law	Block 5: Equality and Justice	Block 6: Technology and Innovation
Online Content					
Exploring Sustainable Development	Science, understanding, and Sustainable Development	Behavior and organization change	Policy	Reintroducing the social pillar of sustainable development	Innovation and purpose
Introduction to the Anthropocene	Qualitative methods	Promoting pro-environmental behavior	Climate change and policy	Inequality, ethics, and sustainable development	Biodesign
Systems thinking and interdisciplinarity	Quantitative methods	Case study: The sea	Sustainability and the law	A history of environmental movements	Storing energy with hydrogen
	Uncertainty in a changing world	Case study: For Ethiopia	The limits of the law	Environmental racism	Sustainable buildings
		NGOs and civil society	Economics: Costing the Earth		Innovation and responsibility
Workshop Activities Linked to Every Block of Online Content					
Group work, voting, arguments in small and large groups, role playing	Group work, online research, voting, negotiation, arguments in large groups, role playing	Online research, working from small groups toward a large group, group presentation	Mock trial, flipped classroom, online research, group work, group arguments, negotiation	Decision making, critical thinking, critical analysis, online research, group work	Group work, online research, elevator pitch, group presentations
Relevance to Chemistry Education in Terms of Content					
H	H	H	H	M	M
Relevance to Chemistry Education in Terms of Skills					
H	H	H	H	H	H

[a]Low (L), medium (M), high (H).

demographics of the learners (e.g., age, student vs external learner, international students vs U.K. based students, and departments and disciplines) but also information on how many engage with the texts, discussion sections, and videos. This is being done online (through information collected by the platform or University of Bristol specific questionnaires) but also offline during workshop sessions with the students that have completed the online course. Additionally, we are collecting information on areas of improvement as well as on the strong features of the course according to the students. This information and internal reports that have been produced so far on each run of the course will be compiled and published at a later stage when the student sample is large enough to be statistically significant.

The SDOU has just completed its first run (April 2019). To evaluate the unit, we are following a method similar to the one used for the online course. We request written, online feedback from the students at the point of completion of their final assessment, and we run offline, student focused workshops where the students can discuss with the lead educators their engagement with the online and offline content, the methods of delivery, the assessments, and their general experience of the unit as a whole. It is still very early to evaluate this unit on the basis of the results of the feedback from the first cohort (250 students), but we believe that after academic year 2019−2020, we will have had enough students take the unit to be able to produce a thorough report that includes the demographics of the students having taken the unit as well as their overall their experience of it. Figure 1 shows an example of the type of feedback collected anonymously through online forms from the students and the types of questions we are using in order to evaluate the impact of the unit.

■ CONCLUSION

We live in a rapidly changing world. Although the function of science has always been to help us understand the natural world around us and to improve our lives using this knowledge and understanding, we are now facing urgent challenges on a global scale that could prove integral for our species very survival. These challenges have been mapped according to the UN under the Sustainable Development Goals. Chemistry has a pivotal, leading role to play in addressing these challenges, but this leading role needs to be reflected in higher education curricula, including the core knowledge, skills, values, and ethos we cultivate in our chemistry graduates. The Bristol Futures educational initiative is attempting to incorporate the themes of Sustainable Development, Innovation and Enterprise, and Global Citizenship across the University of Bristol. This paper focused on the Sustainable Development theme and how this theme can help incorporate sustainable development, systems thinking, and interdisciplinarity specifically into the chemistry curriculum. We present both the Sustainable Futures Massive Online Open Course (MOOC) as well as the Sustainable Development Optional Unit (SDOU), and we discuss how each of these can help the undergraduate chemist understand and embrace interdisciplinarity and systems thinking, to "think" beyond their disciplines, backgrounds, and experiences and understand that addressing global challenges requires collaboration across the traditional silos of academia and policy-making. To stimulate this engagement, we designed the SFOC and SDOU to ensure that the Sustainable Development Goals covered are presented and discussed under broad headings. Throughout the content

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List the two best things about this unit.	Which two aspects of the unit would you change?	Why did you choose this unit?
The interactive workshops, the group activities and public speaking.	The assessment parts of it	I am interested in a career in sustainable development
	More relevant to my degree civil engineering, most was geography based	Didnt like the other ones
The way that we have to apply it to every day life and working in different groups.		It is very interesting and relevant to what I want to do.
Learning about relevant topics	Tasks in the blocks not being in big groups and seminars were too long for tasks	I lik sustainable development
1. I liked how it was all linked to our future 2. I like how although it had challenging aspects it was too hard that I did not understand	1. I think you should complete the discussion groups after completing the blocks not before because you would then have a better understanding	Because it was the one I though I would find most interesting out of the choices
The content was interesting The teaching methods were really good	Get rid of the multiple choice quizes if they dont contribute to the overall mark Maybe put the information about the wiki and everything's expected from it at the beginning rather than after the activities	I think it is a relevant topic and didnt really like the other options i was given

Figure 1. Example of the questions used to collect student feedback on their experience of the unit and some of the anonymous answers provided.

provided, students are encouraged to reflect upon their own contribution to the SDGs; the roles of their home-disciplines; and the importance of engagement with other disciplines, communities, and organizations in addressing global challenges. The successful launch of Sputnik required the expertise of many, and the Sustainable Development Goals are no different. It is by stimulating such a process of reflection, collaboration, and dialogue that a new generation of chemistry graduates can be equipped with the skills necessary to address global challenges.

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Notes

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