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Exploring Curriculum Adoption of Green and Sustainable Chemistry in Undergraduate Organic Chemistry Courses: Results from a National Survey in the United States

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This study sought to explore the integration of green and sustainable chemistry into the organic chemistry curriculum through a national survey of organic chemistry instructors (n = 160) within the United States. It was found that faculty were most familiar with the green chemistry topics of reaction efficiency and catalysis and least familiar with the topics of efficiency metrics and life cycle impacts of chemicals. This unfamiliarity with efficiency metrics and life cycle impacts of chemicals was echoed in a low perceived importance for chemistry and related science students to know these concepts and subsequently its incorporation of green chemistry topics was amongst the lowest of the topics evaluated. Similarly, it was found that most faculty were unaware of the United Nations Sustainable Development Goals and planetary boundaries, and thus the integration of these topics into the curriculum was also low. To identify which factors affected the integration of green chemistry, the survey items were developed using the Teacher-Centered Systemic Reform model. Stepwise linear regression was used to identify which factors significantly affected its integration into the teaching curriculum and assessments. Overall, it was found that that teacher thinking factors held the greatest impact. In addition, departmental requirement or encouragement of green chemistry integration was found to significantly impact its incorporation for both the curriculum and assessments. These results suggest that there is a need both to provide training opportunities for faculty to become more familiar with these topics and their relevance to the organic curriculum and to work with people in leadership roles at the universities to encourage departmental integration.

Introduction

Over the last few decades, there has been a growing emphasis on the need to integrate green chemistry into education. Highlighting this focus, the fourth United Nation Sustainable Development Goal states that by 2030 "all learners acquire knowledge and skills needed to promote sustainable development."[1] This need for green chemistry integration has also been echoed by students around the world. For example, 86% of the respondents from a survey conducted at University of Colorado Boulder indicated that they were either very interested, interested, or a little interested in learning more about green chemistry.[2] Similarly, in a worldwide survey conducted by Students Organizing for Sustainability International, 85% of the respondents indicated they agreed with the statement "Sustainable development is something which I would like to learn more about."[3] Due to student excitement about the topic, green chemistry provides an opportunity to engage students in the curriculum in a meaningful way, thus contributing towards creating more inclusive classrooms.[4] Additionally, reported methods for teaching about green and sustainable chemistry often include the use of active learning, high impact practices, and inclusive teaching strategies, which further promotes inclusivity in the classroom.[4]

Furthermore, the integration of green and sustainable chemistry into the curricula promotes a systems-thinking approach by having students consider the molecular basis of sustainability by thinking about chemicals or reactions both on the molecular level and on the global level by evaluating their impacts on society and the environment.[5] Thus, knowledge of green chemistry is essential not just for the students who will pursue research or industrial jobs in chemically related fields, but by all students because it can provide a platform for connecting the course concepts to solving, or at least thinking about, relevant concrete examples which they can then later apply in their own fields and personal lives.[6] The integration of green and sustainable chemistry into the organic curriculum has recently been reported through laboratory experiments,[7–11] course-based undergraduate research experiences (CUREs),[12] comics,[13] videos,[14] infographics,[15] and student-generated letters to representatives about scientific topics.[16] Additionally, several literature reviews describing the integration of green chemistry into the chemistry curriculum can be found elsewhere.[17–25]

Although the integration of green chemistry has been shown to have many benefits, it remains not well-represented in the textbooks;[26] thus the decision of what to incorporate and how to incorporate it falls on the individual instructors. Therefore, to discover how and what aspects of green and sustainable chemistry are being integrated into the curriculum, a nationwide survey of faculty was necessary. Since it has been reported that the majority (53%) of green chemistry instructional activities published in the *Journal of Chemical Education* were implemented in organic chemistry,[20] we sought to investigate its nationwide integration into this course.

In addition to green chemistry which oriented chemistry towards sustainability, more recent advances to sustainable chemistry include the development of two sustainability frameworks: the planetary boundaries and the United Nations Sustainable Development Goals (UN SDGs).[27] These frameworks allow chemistry to be taught in a more relevant and engaging way since the isolated chemistry facts become explicitly entwined with real-world applications and problems through the integration of systems thinking.[5,28] Systems thinking promotes students to view a system as a whole instead of a collection of independent parts framing the context of chemistry within both social and environmental systems.[29] Recently, York and Orgill reported the five essential characteristics of systems thinking approach in their development of the Characteristics Essential for designing or Modifying Instruction for a Systems Thinking approach (ChEMIST) table.[29] These five characteristics include the following: recognizing a system as a whole instead of a collection of parts; examining the relationships between parts of a system and how the interconnections result in cyclic system behaviors; identifying the variables that cause system behaviors, including unique system-level emergent behaviors; examining how system behaviors change over time; and identifying interactions between a system and its environment, including the human components of the environment.[29] In addition, an evaluation of faculty perceptions of integrating systems thinking into the undergraduate chemistry curriculum has recently been reported by Jackson and Hurst.[30]

Planetary boundaries, originally proposed in 2009 by Rockstrom et al.[31,32] and updated in 2015,[33] describe a safe operating space for sustainable development because they provide a method for quantitative evaluation of the nine impacted Earth system processes.[34] These boundaries include climate change, novel entities, stratospheric ozone depletion, atmospheric aerosol loading, ocean acidification, biogeochemical flows, freshwater use, land-system change, and biosphere integrity.[31] Of these nine processes, as of 2015, the following four boundaries have already been crossed: climate change, loss of biosphere integrity, land-system change, and altered biogeochemical cycles.[33] The incorporation of planetary boundaries into the curriculum provides a platform for teaching systems thinking because it connects reactions learned in the classroom with global implications which provides context for learning the material.[34–36] For example, the planetary boundary "ocean acidification" provides global context for students who are learning acid-base reactions.[37] However, currently there are limited resources available for its implementation and literature accounts describing its implementation are scarce. Progress is being made on this front though as an online interactive learning tool has been developed and is available for use in the classroom.[24]

The United Nations Sustainable Development Goals (UN SDGs), which were adopted by all UN member states in 2015, outline the 17 key global challenges that we currently face and provide achievable targets for combating these challenges.[38] Similar to the planetary boundaries, the UN SDGs have been used as a framework to show how the chemistry concepts taught in class are needed to solve real-world issues which connects chemistry with societal, economic, and environmental systems.[39–42] Framing the material in this manner can help engage students as they see both the interdisciplinary nature of chemistry and how it can be used to create a better future.[35] A review outlining progress in addressing the SDGs within the curriculum using systems thinking can be found elsewhere.[43]

In 2015, the American Chemical Society Green Chemistry Institute (ACS GCI) conducted a survey of chemistry faculty to determine current chemistry teaching practices, perceived importance of teaching green chemistry concepts, and barriers affecting the incorporation of green chemistry into the curriculum.[44] However, this study was conducted several years ago, included a mixture of responses from both high school and undergraduate chemistry instructors, did not specifically focus on the incorporation of green chemistry into organic chemistry courses, and did not address the integration of planetary boundaries or the UN SDGs. Our study was designed to further investigate how green chemistry, planetary boundaries, and the UN SDGs are currently incorporated into the organic curriculum and identify factors affecting their integration using a well-defined sampling frame of organic chemistry faculty.

Theoretical Framework

Questions for the survey were developed with consideration to the Teacher-Centered Systemic Reform model to identify what factors affect the integration of green chemistry into the organic curriculum. The Teacher-Centered Systemic Reform (TCSR) model shows how teachers' implemented instructional practices are shaped by the interrelationship of *contextual factors*, *personal factors*, and the *teacher's thinking about teaching*.[45,46] *Contextual factors* include aspects such as the broader cultural context (i.e. professional organizations, textbooks and teaching materials, and teacher development), institutional context (i.e. type of institution and daily, weekly, and yearly schedule), department and subject area context (subject area and teacher and department demographics), and classroom context (class size, textbooks and materials, and student demographics, abilities, and personal expectations).[45] *Personal factors* include aspects such as demographic profile, types and years of teaching, teacher preparation, and instructor continued learning efforts.[45] Finally, *teacher thinking factors* includes the instructors' knowledge and beliefs about teaching and teachers' roles, students and learning, schooling and schools, content taught, and sense of dissatisfaction with current practices.[45] As shown in Fig. 1, the enacted classroom teaching practices, such as the integration of green chemistry, are impacted by all three inter-related aspects. Within chemistry education, this model has been used to frame a variety of studies including the development of a new faculty workshop on the integration of evidence-based instructional materials[47] and in the development of survey and interview questions to assess faculty's teaching practices.[48–51]

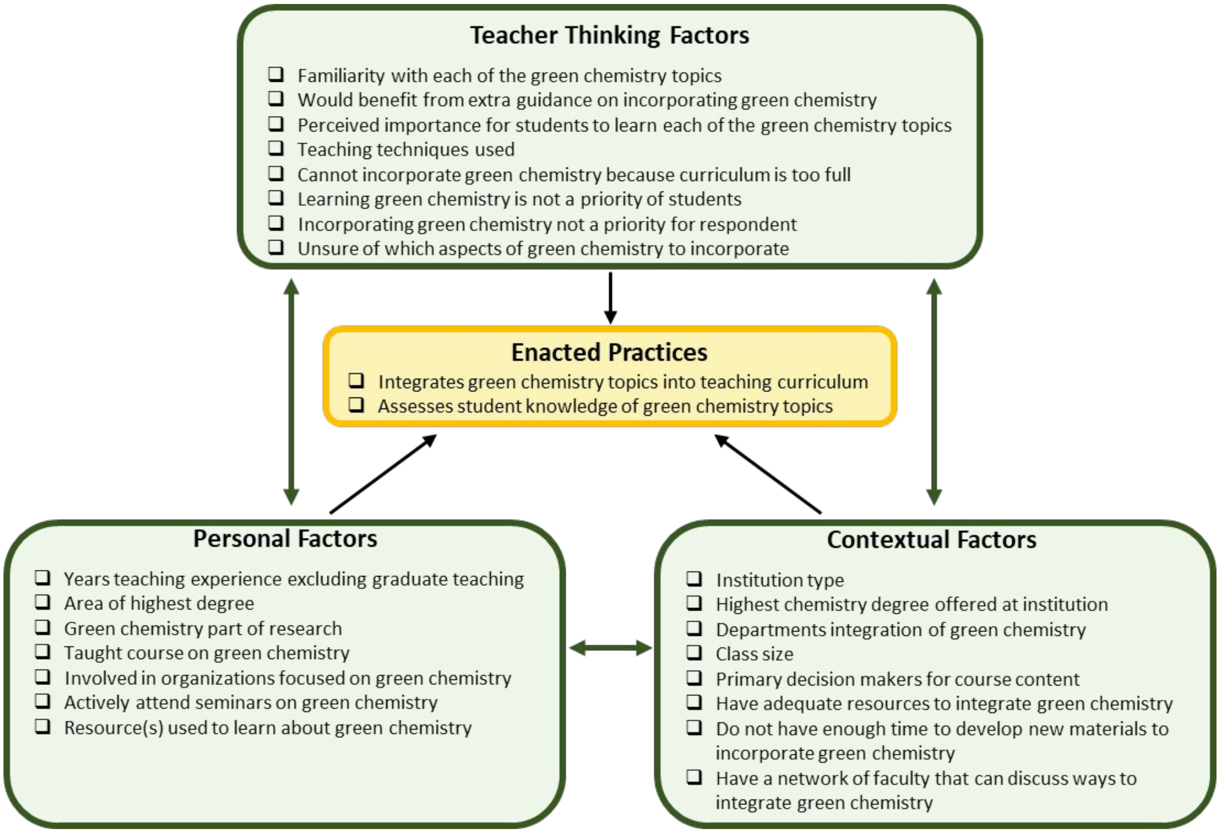

Fig. 1 Teacher-Centered Systemic Reform (TCSR) model

Research Goal

The purpose of this study was to explore how green chemistry is currently incorporated into undergraduate organic chemistry curricula and assessments across the United States and what personal factors, teacher thinking factors, and contextual factors affect its integration. Additionally, we were interested in how the United Nations Sustainable Development Goals (UN SDGs) and planetary boundaries were incorporated into the curriculum.

Methodology

A survey of undergraduate organic chemistry faculty across the United States was conducted via Qualtrics[52] between December 2021 and January 2022. Reminder emails were sent two and four weeks after the initial invitation. This study was conducted with approval from the Institutional Review Board (Protocol # IRB0003449). Informed consent was obtained from all survey respondents.

The survey was developed iteratively. Survey items were based on the constructs outlined in the Teacher-Centered Systemic Reform (TCSR) model (Fig. 1). The level and type of enacted practices were identified by asking respondents to indicate if they implicitly or explicitly address the green chemistry topics in their course curriculum or assessments. To identify the extent that personal context influenced the integration of green chemistry, faculty were asked questions such as number of years teaching, what their highest degree was in, and if green chemistry was part of their research. To identify the extent that contextual factors affected the integration of green chemistry, respondents were asked questions such as if they are required or encouraged by their department to integrate green chemistry, if others in their department incorporate green chemistry, and details about their institution. Finally, to identify the extent that teacher thinking affected the integration of green chemistry, respondents were asked questions such as their familiarity with and perceived importance of students learning the green chemistry topics.

The green chemistry topics addressed in this survey, with the exception of recycling, were obtained from the 2015 survey by the ACS Green Chemistry Institute.[44] After creating the first draft, we received feedback from three external faculty, which resulted in shortening the survey and rearranging the questions so that first familiarity of each concept was assessed, then perception, and finally integration of the concepts into the curriculum. A pilot test of this revised survey was then administered to undergraduate organic faculty across the United States to receive feedback on whether there were unclear survey items or if there were any items they would recommend adding or modifying. Based on the feedback received, we added a definition to distinguish what was meant by explicit and implicit inclusion of green chemistry. The final version of the survey was then administered to all participants.

The final version of the survey instrument consisted of 37 questions which assessed their knowledge and integration of green and sustainable chemistry and 18 demographic questions. For transparency and potential adoption, the full survey is provided in the Supplemental Materials. Since the survey did not contain forced answers and since not all respondents saw all 37 survey questions due to only applicable follow-up questions for a prompt appearing, the response rate for individual items varied and will be reported when addressing the item.

Survey Respondents and Data Collection

Participants were selected by compiling a list of undergraduate organic chemistry faculty from a series of digital resources. First, organic chemistry faculty members listed on the Organiclinks[53] and OrganiclinksPUI[54] databases who were not retired were invited via email to participate in the survey. If the faculty member had retired, the current organic chemistry faculty for that university were identified using their department's webpage. If the faculty member had moved, both their contact information at their new university and that of the current organic chemistry professor(s) for their original university was added to the database. Next, organic chemistry faculty who taught at schools whose ACS student chapter won the green chemistry award were identified and invited to participate in the survey. Finally, an independent search of undergraduate organic faculty from universities across the United States who had not already been identified were added to the database.

The survey was sent to 1,726 undergraduate organic chemistry faculty across the United States. A total of 179 respondents started the survey, 160 respondents completed parts of the survey, and 149 respondents completed the whole survey. Responses for the demographic questions were provided by 149 of the 160 respondents. Of the 149 respondents, 56% taught at a public university and 44% taught at a private university. Furthermore, 6% taught at an institution where the highest degree offered in chemistry is an associate degree, 48% at an institution that offered a baccalaureate degree in chemistry, 31% were at an institution that offered a master's degree in chemistry, 13% were at an institution that offered a doctoral degree in chemistry and 2% were at an institution that does not offer a chemistry degree.

Of the 148 respondents who indicated the area of chemistry in which they received their highest degree, 85% indicated it was in organic chemistry, 5% in inorganic chemistry, 3% in biochemistry, 2% in chemistry education, and 5% in other fields of chemistry. On average, the respondents had taught for 20 years excluding graduate school teaching with a reported range of 3-53 years of teaching experience.

Statistical Analysis

Descriptive and inferential statistics were calculated using StataIC 16.[55] Likert items for which agreement indicated that it was less likely for green chemistry to be integrated were reverse coded so that an increase in value would correspond to being more likely to incorporate green chemistry. Due to the limited number of responses for faculty's area of highest degree outside of organic chemistry, for regression analysis the data were combined to form only two groups for highest degree: organic chemistry and other. Furthermore, to allow for regression analysis responses for three of the contextual factors were dichotomized. The highest chemistry degree offered at the institution item was used as a proxy for research versus teaching focus since instructors who teach in institutions which offer graduate degrees in chemistry typically have a greater focus on research than those that do not.[56,57] Therefore, responses were categorized as offering either no degree, associate, or baccalaureate degrees or as offering either master's or doctoral degrees. Additionally, for the department's integration of green chemistry, responses for required integration and encouraged integration were combined into one category to dichotomize the data. Finally, responses for class size were broken into two categories: those with less than 100 students and those with more than 100 students. All other survey items were used without further modification.

Results & Discussion

Faculty's Familiarity with and Perceived Importance for Chemistry and Related Science Graduates Knowledge of the Green Chemistry Topics

Faculty responses received about their familiarity with a series of green chemistry topics are shown in Fig. 2(a). With the exception of the topic recycling, these green chemistry topics were previously reported in the survey study by MacKellar *et al.*[44] Based on the responses collected for this item (n = 158), the most known green chemistry topic was catalysis with 87% being either familiar or very familiar with the topic. Meanwhile, the least known green chemistry topic was the life cycle impacts of chemicals with only 46% of the respondents indicating that they were either familiar or very familiar with the topic. Life cycle impacts of chemicals refers to understanding how chemicals are produced and the social, environmental and economic impacts of their extraction or manufacture.[44] Within chemistry education, students can be taught about life cycle analysis through analyzing the source of the chemicals used, the solvents and catalysts selected, and the fate, toxicity, and waste generated from the products.[58] Despite availability of resources for integrating life cycle analysis,[58] the percentage of faculty being familiar with this concept remains low. Finally, as illustrated in Fig. S1, when asked how the respondents learned about the green chemistry topics, the most common response was through journal articles (71%) followed by conferences (53%).

Furthermore, because what faculty perceive to be important for chemistry and related science graduates to know about affects what they integrate into their curriculum, the respondents (n = 154) were asked to indicate their perceived importance for each of the green chemistry topics, shown in Fig. 2(b). Amongst the topics, most faculty agreed that being knowledgeable about chemical hazards and exposure was either extremely (61%) or very important (27%) for chemistry and related science graduates to know; however, the other topics received a mixture of responses ranging from extremely important to not at all important. This finding for the high perceived importance of students knowing chemical hazards and exposure matches the findings from the 2015 ACS GCI survey in which most respondents (84%) from all fields and educational levels indicated this as essential to know.[44]

Surprisingly, the topic of efficiency metrics, which involves calculating the efficiency of a reaction or process through equations such as process mass intensity or atom economy, received the least respondents classifying it as either extremely or very important (36%). Similarly, reaction efficiency and process efficiency also experienced a large decline in perceived importance for students to know the material when compared to faculty familiarity with the topics. This is in stark contrast to topics that are more closely aligned with environmental impact such as chemicals in the environment, chemical hazards and exposure and lifecycle impacts of chemicals; where faculty familiarity approximately matched their perceived importance for students to know the material. This contrast between familiarity and perception for mass based or efficiency metrics topics may be attributed to several possible reasons. One possibility is that while familiar with the topic, the instructors do not feel sufficiently equipped to teach the subject which lowers their perceived importance for students. Another possibility is that instructors may not consider that efficiency metrics are valid measures of the environmental impact since mass-based metrics do not address how harmful a synthesis is, so prefer that their students focus on topics such as chemicals in the environment, chemical hazards and exposure and lifecycle impacts of chemicals. Finally, while the topics that are closely aligned with environmental impact have relatively concise measures, topics addressing efficiency metrics have a wide range of calculations which may limit instructors perceived importance for student knowledge of them especially since new metrics are continually being added. The precise reason for this discrepancy will need to be further evaluated in future qualitative studies.

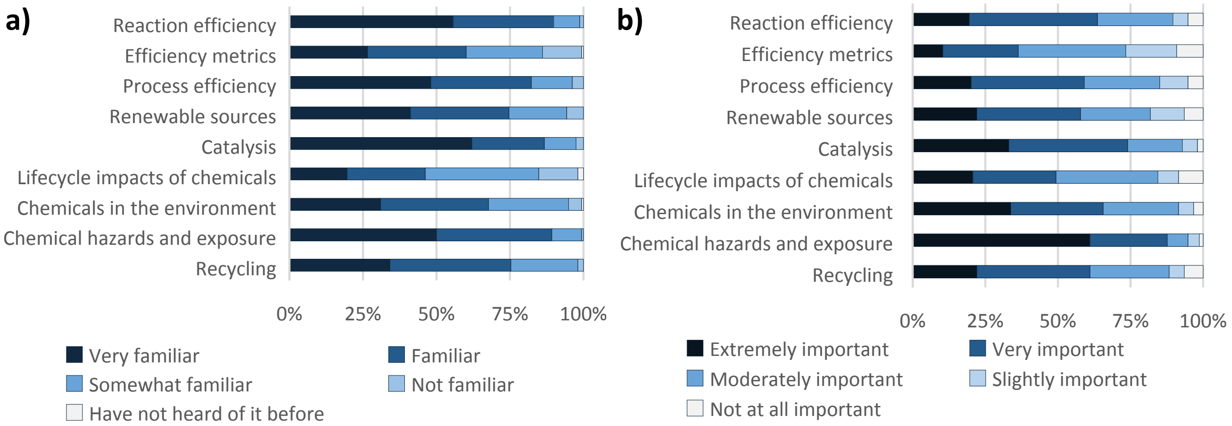

Fig. 2 Faculty's familiarity with (a) and perceived importance of chemistry and related science students knowing about (b) green chemistry topics

Green Chemistry Topics Addressed Either Explicitly or Implicitly in Classroom Activities and Assessments and Feedback Received

The instructors were then asked if they either explicitly or implicitly addressed the green chemistry topics in their classroom activities. Prior to asking about their integration of green chemistry, the definitions for explicit and implicit instruction were provided. Explicit instruction was defined as "providing clear learning goals for the topic and actively integrating it into the classroom activity and/or course assessments." Additionally, implicit instruction was defined as "presenting the topics without defining clear learning goals for them. The topic is addressed, but in the background, and not the focus of the classroom activity and/or course assessment." As shown in Fig. 3(a) the topic that most faculty address in their classroom activities was catalysis with 33% of the respondents addressing it implicitly and 52% addressing it explicitly; however, in the findings from the 2015 survey conducted by the ACS GCI, the most taught concept within organic chemistry was reaction efficiency.[44]

Interestingly, while instructors indicated perceived importance for students to know the topics addressing environmental impacts including life cycle impacts of chemicals and chemicals in the environment, the percent of instructors incorporating these topics into their classroom activities is much smaller which may indicate a need for the development of educational materials that instructors can use in their courses. In fact, the concept of life cycle impacts of chemicals was the least commonly addressed topic with 34% of the respondents addressing it implicitly and only 10% addressing it explicitly. This limited emphasis on the life cycle impacts of chemicals is in accordance with findings from the 2015 survey which found that the two equally least commonly taught concepts in organic chemistry were life cycle impacts of chemicals and renewable sources.[44] Our results differ slightly from those of the 2015 survey in that renewable sources was addressed slightly more than life cycle impacts.[44] However, it is not surprising that catalysis is the most commonly addressed topic and the life cycle impact of chemicals is the least commonly addressed since they are also the most widely known (87%) and least commonly known (46%) green chemistry topics amongst the respondents.

As shown in Fig. 3(b), respondents were much less likely to incorporate the green chemistry topics in their student assessments than in their classroom activities. Thus, although faculty indicated their perceived importance of students knowing the green chemistry topics and valued the topics enough to integrate them into the course activities, it is not reflected in the assessment content; creating a mismatch in alignment between what is taught and what is assessed. This is of particular importance because the nature of assessments has been shown to strongly indicate to students what is important to learn in the course and where they should focus their studies,[59] so this lack of constructive alignment may hinder students learning of the green chemistry topics. This, in part, can be also attributed to the lack of available assessment tools for the evaluation of students' knowledge of green chemistry knowledge aligned with instructors' goals. While several assessment instruments are available for research purposes,[60,61] there is a need to develop high-quality customizable assessments that could help measure success of implementation of new green chemistry curricula.

While we did not ask respondents whether their institution uses the exams from the ACS Examination Institute within their course, nationwide approximately half of the institutions do use them in some capacity.[62] Due to the number of survey responses received, it is reasonable to assume that this would hold true for our sample as well. It has been reported that recent organic chemistry exams by the ACS Examination Institute typically only contain one item in which green chemistry is mentioned, but in almost all instances this item could be solved without specific knowledge of the green chemistry principles.[26] Despite its small weight of the exam, the ACS does include it as one of the required concepts to be taught within ACS certified chemistry degrees;[41] further illustrating the disjointed nature between teaching and assessing students' green chemistry knowledge.

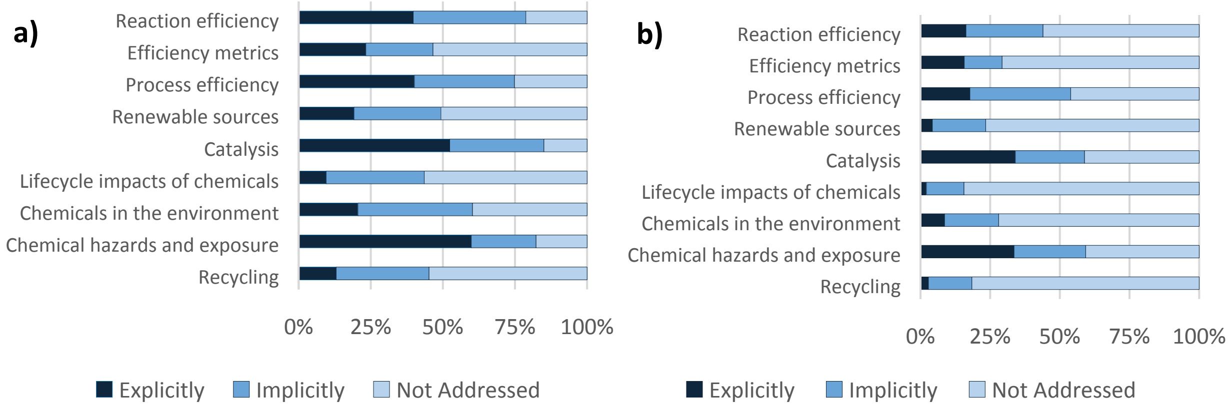

Fig. 3 Frequency green chemistry topics are addressed explicitly or implicitly in classroom activities (a) and assessments (b)

Of the 151 respondents who incorporated at least some of aspects of green chemistry into their curriculum, 26% indicated that they received feedback on its integration from students, colleagues, and/or administration. Amongst those who received feedback from students (*n* = 31), 84% of the respondents received either only positive or mostly positive feedback from their students and 16% received mixed positive and negative feedback from their students. Similarly, for those who indicated that they received feedback from their colleagues (*n* = 26), 81% received either only positive or mostly positive feedback from their colleagues, whereas 19% received mixed positive and negative feedback. Finally, only one respondent indicated that they received feedback from their administration which was mostly positive. In each of these instances, the type of reported feedback was subjective due to the nature of the survey, and therefore, may warrant future in-depth qualitative investigation.

Faculty's Familiarity, Perceived Importance, and Integration of Planetary Boundaries

Of the 157 respondents who answered the item assessing their familiarity with planetary boundaries, only 4% indicated that they are knowledgeable about the planetary boundaries and can relate them to organic chemistry. Furthermore, only 3% indicated that they are familiar with the planetary boundaries but not sure how to relate them to organic chemistry, and 7% indicated that they have heard of the planetary boundaries, but do not know what they are. Finally, 86% indicated that they have not heard of the planetary boundaries. When those who at least heard about the planetary boundaries (*N* = 22) were further prompted to indicate how they learned about them, the most common method was online resources (57% of respondents), followed by organization resources (22%).

Next, to assess faculty's perceived importance for chemistry and related science students to be knowledgeable about the planetary boundaries, respondents were provided with the definition and list of planetary boundaries and then asked to indicate its importance. Only 15% of the respondents indicated that it was either extremely or very important, whereas 54% indicated it was only slightly or not at all important for the students to learn about the planetary boundaries. Due to the low percentage of respondents indicating that they are familiar with the planetary boundaries and find learning about them valuable for the students, it is not surprising that none of the respondents explicitly incorporate the planetary boundaries into their curriculum and only 11 of the 149 respondents (7%) incorporate some aspects of planetary boundaries into their curriculum. Of those that do incorporate some aspects of planetary boundaries, only approximately one-third incorporate them into their assessments with two indicating they include them on their exams and two indicating they include them either through informal classroom observations or implicitly in assessments. These results indicate that the concept of planetary boundaries is novel for many organic faculty which may limit their perceived importance for students to learn about them and may require training opportunities for further integration into the curriculum.

Faculty's Familiarity, Perceived Importance, and Integration of United Nations Sustainable Development Goals (UN SDGs)

Of the 159 respondents who answered the prompt assessing their familiarity with the UN SDGs, only 20% indicated that they are knowledgeable about the UN SDGs and can relate them to organic chemistry. Furthermore, 9% indicated that they were familiar with the goals but not sure how to relate them to organic chemistry, and 28% indicated that they have heard of the goals, but do not know what they are. Surprisingly, 43% indicated that they have not heard of the UN SDGs. Of those that had indicated they had at least heard of the UN SDGs (*N* = 91), the most common method for learning about them was through online resources (28%). The frequency of other reported methods for learning about the UN SDGs is shown in Fig. S2.

To assess faculty's perceived importance for chemistry and related science students to be knowledgeable about the UN SDGs, respondents were provided with the definition and list of the UN SDGs and then asked to indicate its importance. Only 23% of the respondents indicated that it was either extremely or very important for chemistry and related science students to be knowledgeable about the UN SDGs, whereas 42% indicated it was only slightly or not at all important. Again, due to the low level of familiarity and perceived importance, it was not surprising that only 1% of the respondents indicated that they explicitly incorporate the UN SDGs into their curriculum and only 21% incorporate some aspects of the UN SDGs into their curriculum.

For those that do incorporate the UN SDGs, the most common methods for assessing student knowledge of them include informal classroom observations (*n* = 8), followed by homework/assignments (*n* = 7), student projects (*n* = 7), and lab reports (*n* = 7). These results indicate that along with planetary boundaries, the UN SDGs are also a novel concept which may require additional training opportunities for further integration into the curriculum. This need for further learning opportunities is echoed by the respondents, with 68% of the respondents indicating they either strongly agreed or agreed to the statement that they would like to have a network of faculty with whom they could discuss ways to incorporate green chemistry into their curriculum.

Factors Affecting the Integration of Green Chemistry

In an open response question, faculty were asked to identify which factors affect the incorporation of green chemistry into their curriculum. Amongst the responses received (*n* = 128), the most common reason provided was finding time to fit it into a curriculum which is already full (*n* = 44). Other common reasons included finding suitable labs (*n* = 11), having time to develop the materials (*n* = 11), and lack of available materials (*n* = 10). These findings correspond to those obtained by the 2015 ACS GCI survey, which indicated that crowded curricula, lack of funding, and lack of training and educational resources were the commonly reported barriers to the integration of green chemistry across the various chemistry curricula.[44] While much less common, a few respondents provided factors which promoted its integration including that it engages students (*n* = 4) and that it is important to cover (*n* = 4). For a complete listing of all commonly identified factors that limit or promote its incorporation refer to Fig. S3 and Fig. S4, respectively.

To further evaluate which personal, contextual, and teacher thinking factors affect green chemistry's integration into the curriculum and its assessment, inferential analysis was conducted using a stepwise linear regression (*p* = .05) to evaluate the responses to the items outlined in Table 1. Twenty-three factors – seven personal, eight contextual, and eight teacher thinking – were examined using stepwise multiple linear regression. Prior to regression, factors where agreement indicated that it was less likely for green chemistry to be integrated were reverse coded.

Table 1 Factors used in the model and their coding used for regression analysis

Factor	**Coding**
Dependent variables	
Teaching green chemistry	Explicitly integrated = 2, Implicitly = 1, Not integrated = 0; the average of the scores for each green chemistry topic was used
Assessing green chemistry knowledge	
Personal Factors	
Years teaching experience excluding graduate teaching	Reported number of years
Area of highest degree	Organic Chemistry = 1, other = 0
Green Chemistry part of research	Yes = 1, no = 0
Taught course on green chemistry	Yes = 1, no = 0
Involved in organizations focused on green chemistry	Strongly agree = 4, agree = 3, disagree = 2, strongly disagree =1
Actively attend seminars on green chemistry	Strongly agree = 4, agree = 3, disagree = 2, strongly disagree =1
Methods used to learn about green chemistry	
- Conferences	Yes = 1, no = 0
- Seminars	Yes = 1, no = 0
- Workshops	Yes = 1, no = 0
- Coursework (undergraduate or graduate)	Yes = 1, no = 0
- Peer network	Yes = 1, no = 0
- Organization resources	Yes = 1, no = 0
- Online resources	Yes = 1, no = 0
- Journal articles	Yes = 1, no = 0
- Textbooks	Yes = 1, no = 0
Contextual Factors	
Institution type	Public = 1, private = 0
Highest chemistry degree offered at institution	No degree, Associate, or Baccalaureate = 0, Master's or Doctorate = 1
Departments integration of green chemistry	Required or encouraged integration = 1, integration neither encouraged nor discouraged = 0
Class size	<100 students = 1, >100 students = 0
Primary decision makers for course content	Respondent = 4, respondent + one other = 3, respondent + several others = 2, someone or several other people = 1
Have adequate resources to integrate green chemistry	Strongly agree = 4, agree = 3, disagree = 2, strongly disagree =1
Do not have enough time to develop new materials to incorporate green chemistry.	Strongly agree = 1, agree = 2, disagree = 3, strongly disagree = 4
Have a network of faculty that can discuss ways to integrate green chemistry.	Strongly agree = 4, agree = 3, disagree = 2, strongly disagree =1
Teacher Thinking	
Familiarity with each of the green chemistry topics	Very Familiar = 5, familiar = 4, somewhat familiar = 3, not familiar = 2, have not heard of it before = 1
Would benefit from extra guidance on incorporating green chemistry.	Strongly agree = 1, agree = 2, disagree = 3, strongly disagree = 4
Perceived importance for students to learn each of the green chemistry topics	Extremely important = 5, very important = 4, moderately important = 3, slightly important = 2, not important = 1
Teaching techniques used	
- Lecture	Yes = 1, no = 0
- Think-pair-share	Yes = 1, no = 0
- Just-in-time teaching	Yes = 1, no = 0
- Peer-led team learning	Yes = 1, no = 0
- Teaching with case studies	Yes = 1, no = 0
- Process orientated guided inquiry learning	Yes = 1, no = 0
- Problem-based learning	Yes = 1, no = 0
- Flipped classroom	Yes = 1, no = 0
Cannot incorporate green chemistry because curriculum is too full.	Strongly agree = 1, agree = 2, disagree = 3, strongly disagree = 4
Learning green chemistry is not a priority of students.	Strongly agree = 1, agree = 2, disagree = 3, strongly disagree = 4
Incorporating green chem not priority for respondent.	Strongly agree = 1, agree = 2, disagree = 3, strongly disagree = 4
Unsure which aspects of green chemistry to incorporate.	Strongly agree = 1, agree = 2, disagree = 3, strongly disagree = 4

First, the significance of the factors for the integration of green chemistry into the teaching curriculum was analyzed. The resulting model from this analysis will be referred to as the "teaching model." Next, the significance of the factors for the assessment of students' green chemistry knowledge was analyzed. The resulting model from this analysis will be referred to as the "assessment model." Due to the small number of faculty who incorporate planetary boundaries and the UN SDGs, we did not use regression analysis to investigate the factors which affect their integration.

Appropriateness of use of multiple linear regression for this analysis was established by checking the model assumptions for each of the two models. The assumption of linearity was established for both models via analysis of the residual plots. The Breusch-Pagan test was used to confirm the homogeneity of variance assumption for the teaching model (p = .317) and the assessment model (p = .407), and the Shapiro-Wilk test confirmed the assumption of normality (p = .559) for the teaching model. However, for the assessment model the Shapiro-Wilk test came back significant (p = .00005). Thus, to establish normality for the assessment model a histogram of the residuals was generated which indicated that the variance is normally distributed as the histogram appeared roughly symmetric and bell-shaped. Furthermore, analysis of Cook's distance indicates that none of the observations were contributing undue or excessive influence since the maximum Cook's distance for the teaching model was 0.09 and for the assessment model was 0.15 which are both less than 1. Finally, analysis of the variance inflation factor (VIF) indicated that collinearity was not an issue with these predictors as the largest VIF for any of the predictors was 1.12 for the teaching model and 1.26 for the assessment model, which is well below even the most stringent reference value of 5.

The factors identified as significant in the teaching model were found to account for approximately 49% of the variability in the dependent variable (R^2 = 0.4937, p < .0001). As shown in Table 2, these factors largely revolved around teacher thinking and included how important they felt the material was for the students to learn (b = .194, β = .330, p < .0001), their familiarity with the green chemistry topics (b = .222, β = .297, p < .0001), the belief that they cannot incorporate green chemistry because the curriculum is too full (b = .097, β = .177, p = .008) and whether their department required or encouraged its integration or did not (b = .219, β = .196, p = .003), which was the only contextual factor identified as significant. Interestingly, incorporation of the active learning technique Process Oriented Guided Inquiry Learning, or POGIL for short, (b = .280, β = .201, p = .002), and the use of lecture (b = .272, β = .117, p = .037) were also significantly correlated with the integration of green chemistry.

Table 2 Factors identified as significant for the Teaching model[a]

Predictor Variable	*b*	*t*	β	*p*
X1: Average perceived importance for students knowing the green chemistry topics	.194	4.96	.330	<.0001
X2: Average familiarity of the faculty with the green chemistry topics	.222	4.58	.297	<.0001
X3: Using POGIL as a teaching technique	.280	3.19	.201	.002
X4: Departmental encouragement of the incorporation of green chemistry	.219	3.01	.196	.003
X5: Belief that curriculum is too full to integrate green chemistry[b]	.097	2.67	.177	.008
X6: Using lecture as a teaching technique	.272	2.10	.117	.037
Intercept	-1.23	-5.04	-	.000

[a]$F(6, 135) = 21.94$, p < .0001 [b]Factor reverse coded for linear regression.

The two factors "addressing faculty's perceived importance for chemistry and related science students to know the green chemistry topics" and "their familiarity with the topics" were both expected to impact the integration of green chemistry into the teaching curriculum. This is because familiarity with a topic is essential to be able to teach it and perceived importance of a topic will influence the degree to which it is incorporated into the curriculum. Similarly, the belief that the curriculum is too full to integrate green chemistry would be expected to limit its incorporation. It is also not surprising that if a department requires or encourages the integration of green chemistry, the faculty would be more likely to incorporate it when compared to those whose department does not require or promote its integration.

However, the use of POGIL and lecture as a teaching technique being a significant factor were more surprising. POGIL, or Process Oriented Guided Inquiry Learning, is a research-based pedagogic strategy which utilizes a small group, lecture-free instructional method in which students develop their process skills such as critical thinking, communication, and teamwork while engaging in guided inquiry learning.[63,64] The use of POGIL in organic chemistry has been shown to enhance student content knowledge.[65] While incorporating POGIL is correlated with teaching green chemistry, POGIL workbooks have limited integration of green chemistry,[26] but some POGIL activities addressing green chemistry are available.[66] Thus, the connection between using POGIL and incorporating green chemistry should be explored further in future qualitative studies. Finally, the use of lecture as a technique may promote integration of green chemistry as lecture allows for more content to be covered in less time. Further research is needed to establish why these two teaching techniques were significant.

As shown in Table 3, the six factors identified as significant in the model for assessing student knowledge of green chemistry were found to account for approximately 43% of the variability in the dependent variable ($R^2 = 0.4314$, $p < .0001$). Interestingly, only three of the factors identified for integrating green chemistry into the teaching curriculum was found significant for integrating it into assessments. However, like the prior model most of the six factors found significant corresponded to teacher thinking factors. These factors included believing the curriculum is too full to incorporate green chemistry ($b = .145$, $\beta = .282$, $p < .0001$), departmental encouragement of the incorporation of green chemistry ($b = .159$, $\beta = .154$, $p = .036$), the belief that learning green chemistry is not a priority of students ($b = .106$, $\beta = .193$, $p = .016$), and the perceived importance of chemistry and other related science majors knowing about the green chemistry topics ($b = .082$, $\beta = .150$, $p = .043$). Like the prior teaching model, the integration of a teaching technique – think-pair-share ($b = .175$, $\beta = .180$, $p = .013$) – was found to correspond with assessing student knowledge of green chemistry. Finally, the only personal factor that was found significant was learning about green chemistry through journals ($b = .203$, $\beta = .199$, $p = .004$).

Table 3 Factors identified as significant for the Assessment model[a]

Predictor Variable	*b*	*t*	β	*p*
X1: Belief that curriculum is too full to integrate green chemistry[b]	.145	3.66	.282	<.0001
X2: Departmental encouragement of the incorporation of green chemistry	.159	2.12	.154	.036
X3: Learning about green chemistry through reading journal articles	.203	2.93	.199	.004
X4: Belief that learning green chemistry is not a priority of students[b]	.106	2.44	.193	.016
X5: Using think-pair-share as a teaching technique	.175	2.53	.180	.013
X6: Average perceived importance for students knowing the green chemistry topics	.082	2.05	.150	.043
Intercept	-.657	-4.10	-	0.00

[a] $F(6, 129) = 16.31$, $p < .0001$ [b] Factor reverse coded for linear regression.

Regarding the integration of green chemistry into assessments, the instructors' perceived importance for chemistry and related science students knowing the material was again a significant factor since faculty tend to assess the material that they deem most important. Similarly, the belief that the curriculum is too full to integrate green chemistry would again be expected to limit its incorporation in assessments since if it is not incorporated it would not be assessed. Finally, the departmental encouragement or requirement of the incorporation of green chemistry again aided in its integration. There were also three new factors which were not significant for the teaching model. The first was the belief that learning green chemistry is not a priority of students. This may be due to being willing to incorporate it into the lectures even if not a priority for students, but not assessing it since the faculty felt it is a low priority for students. Additionally, learning about green chemistry through reading journal articles enhanced its integration. This may be due to research-led teaching or because faculty who are interested enough in green chemistry to pursue it in the literature are also more likely to perceive it as more important for students to learn and thus incorporate it into their assessments.

Finally, using think-pair-share as a teaching technique was found to be a significant factor. Think-pair-share is a collaborative learning strategy, originally proposed by Lyman in 1981,[67] in which students first think about a posed prompt or question, then pair with a classmate and discuss their responses, and finally share their group's response with the class.[64] Since its initial report it has been used extensively with students ranging from elementary school to college. Within the context of green chemistry, an example of think-pair-share would be to ask students a question such as "What factors might be taken into consideration when choosing which of two proposed reaction schemes is greener?", have students think first individually, then partner with a classmate, and finally share their response as a class either verbally or through polling software such as clickers. The significance of the think-pair-share strategy on the integration of green chemistry may be due to it being an informal assessment technique that faculty are using to assess student knowledge of green chemistry. Further in-depth qualitative studies are needed to confirm why these factors are significant.

Implications for practice

Because teacher thinking factors were found to hold the greatest impact on the incorporation of green and sustainable chemistry, future work should focus on promoting teachers' awareness of and commitment to integrating green and sustainable chemistry. Timely efforts to increase awareness of planetary boundaries and the UN SDGs are of particular importance because most of the respondents were unfamiliar with them. These training opportunities can occur through online communities such as the Green Chemistry Teaching Learning Community,[68] through further incorporation of green chemistry into textbooks,[26] or through intentional media coverage such as the Chemical and Engineering News magazine.[69]

Furthermore, there is a need for institutional adoption of green and sustainable chemistry since departmental encouragement or requirement of its integration was found to have a significant impact on its adoption into the curriculum. Universities which already have department wide integration of green chemistry include the University of California Berkeley,[70] University of Toronto[71,72] University of York,[43] Gordon College,[70] and many other Green Chemistry Commitment signers.[73,74]

Finally, the limited incorporation of the green chemistry topics into instructors' assessment of the content calls for the development of content specific diagnostic tools that measure student knowledge of green chemistry. Despite green chemistry being identified as a key idea to be included by the ACS Approval Program, the organic chemistry exams from the ACS Examination Institute contain at most one question that students can correctly answer without knowledge of green chemistry.[26] Since assessments often indicate to students the important material to learn, the assessments used must reflect the importance of learning green chemistry. Thus, it is essential that other assessments be developed, evaluated, and widely disseminated to address this need.

Limitations and future work

There were several key limitations associated with this study. First, this study was limited to respondents from the United States and therefore should not be generalized to the population of organic chemistry instructors outside the United States. Even with regards to its integration in the US, it may not represent the complete picture for the integration of green chemistry. This is due to a few factors. First, there was a risk of sampling error in the form of under coverage as the sampling frame may have been smaller than the true population.[75] Next, as participants for this online survey were invited only via invitation e-mails, there is a high risk of non-contact which may have resulted in unit nonresponse.[75] Lastly, there was a potential for non-response bias. This survey had a low response rate, albeit comparable with other faculty survey studies,[48,56,76] which may be attributed to faculty who are not interested in integrating green chemistry into the curriculum deciding not to complete the survey. Thus, these survey results may overestimate the actual rate of integration. Furthermore, there was limited participation from faculty at two-year colleges due to difficulties in identifying a complete sample of organic faculty to contact.[56] Finally, it should be noted that there is the potential for interaction effects, such as moderation which occurs when the relationship between two variables depends on a third variable,[77] among the factors. This should be an area for further research.

Due to the close-ended nature of the questions of the survey, we were only able to speculate on reasons why certain factors were significant for the integration of green chemistry. Furthermore, due to the survey format, respondents' interpretation of whether the feedback received about the integration of green chemistry was positive or negative was based on the subjective judgement of the participant without specific details collected. Future work will involve a deeper qualitative investigation of the integration of green chemistry, feedback received about its integration, and factors affecting its incorporation through faculty interviews.

The survey has been provided in the SI, in hopes that researchers can use its questions in part or in whole to conduct similar investigations of green chemistry integration into the curriculum of other countries. Furthermore, the survey can be used as a measure of success of the educational initiatives that are aimed to enhance the implementation of green education at the post-secondary level. Finally, around the globe many universities are now offering graduate degrees and certificates in green chemistry.[78] Therefore, it would be worthwhile to conduct a similar investigation into which aspects of green and sustainable chemistry the faculty are emphasizing in their curriculum. This may provide further guidance into what aspects of green chemistry should be incorporated into the undergraduate curriculum.

Conclusions

In this study, a nationwide survey was conducted with organic chemistry faculty (n = 160), who teach in the United States, to investigate the incorporation of green chemistry into the organic curriculum and identify factors that affect its incorporation. It was found that faculty were most familiar with the green chemistry topics of reaction efficiency and catalysis, while they were least familiar with the topics of efficiency metrics and life cycle impacts of chemicals. This unfamiliarity with efficiency metrics and life cycle impacts of chemicals was echoed in a low perceived importance for chemistry and related science students to know these concepts and subsequently its incorporation of green chemistry topics was amongst the lowest of the topics evaluated. Furthermore, it was found that most respondents were unaware of the UN Sustainable Development Goals and the planetary boundaries which corresponded to an exceptionally low integration of these concepts. Thus, there is a need for these topics to be widely publicized and for faculty training opportunities on these concepts, their importance, and their use in the curriculum.

To identify factors affecting the integration of green and sustainable chemistry a free response question and a series of closed response items were incorporated. Through analysis of the close-ended responses using the Teacher-Centered Systemic Reform model, it was found that teacher thinking factors had the greatest impact on the integration of green and sustainable chemistry into the curriculum and the assessments. Three factors, two teacher thinking and one contextual, were found to be significant for both its integration into the teaching curriculum and into assessments. The two teacher thinking factors included their perceived importance for chemistry and related science students to learn the concepts and if they believe that the curriculum is too full to integrate green chemistry. This belief about the curriculum already being too full was also the most frequent factor provided to the free response question lending evidence to the validity of the results. The only contextual factor found significant to both the integration of green chemistry into the teaching curriculum and assessment was if the department required or encouraged the integration of green chemistry into the curriculum. Furthermore, three teacher thinking factors were found significant only for the integration of green chemistry into the teaching curriculum. These included the average familiarity of faculty with each of the concepts and the use of POGIL or lecture as the teaching method. Similarly, teacher thinking factors found significant for the integration of green chemistry into assessments included if they held the belief that learning green chemistry is not a priority of students and using think-pair-share as a teaching technique. Furthermore, the personal factor of learning about green chemistry through reading journal articles was found significant for its integration in assessments. Overall, since teacher thinking factors held the greatest impact on the integration of green chemistry, it is recommended that professional development opportunities focus on addressing these topics. Additionally, as the value that the department puts on green chemistry integration has a significant impact, there is a need for change agents to promote its value to people in leadership roles at universities. In conclusion, it is our hope that the results of this study coupled with the reviews by Chen et al.,[17] Li and Eilks,[19] Marques et al.,[20] and Savec and Mlinarec[25] can inform the development of professional development opportunities and both curriculum and assessment materials aimed at engaging students with green chemistry.

Conflicts of Interest

There are no conflicts to declare.

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