Student-Led Incorporation of Green Chemistry into Introductory Chemistry (CHEM 1021) Course

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Executive Summary

Over the past few decades, the need for green chemistry implementation within organizations, industry, and education institutions alike has only become more apparent. Industry has called for an integration of green chemistry and sustainability principles “into chemistry, engineering, science and business curricula” (GC3) and the National Science Foundation (NSF) has encouraged incorporation of sustainable chemistry into research proposals seeking funding.

Futhermore, education and application of green chemistry principles is aligned with the goal of the University of Colorado Boulder (CU Boulder) to be a global leader in sustainability and the university’s’ strategic imperatives to “shape tomorrow’s leaders, be the top university for innovation, and positively impact humanity”. Students at CU Boulder have shown a strong interest in learning green chemistry principles. Through three previous survey efforts that the CU Boulder Green Labs Program conducted in collaboration with the CU Boulder Chemistry Department, student interest and previous engagement with green chemistry was evaluated. In the most recent survey (Fall 2021), 48% of students reported that green chemistry was never mentioned, and 28% of the students selected that green chemistry was spoken about once in the semester. Additionally, when students were asked if they would have liked to see more green chemistry topics mentioned in their courses 81% replied: “yes”. These results demonstrate that despite having the majority of respondents interested in learning about green chemistry in their courses, students had very little exposure to the material.

In response to the results of the survey efforts, members of CU Green Labs and the Chemistry Department collaborated to create a green chemistry education pilot program in the Spring 2021 semester that focused on implementing green chemistry into Introductory Chemistry - CHEM 1021. This course was chosen due to the wide variety of student majors it reaches each year, and the fact that there was one course instructor to help streamline the process of the pilot. The pilot consisted of 10 green chemistry focused modules in the form of quizzes, each with 10 questions, that explored a variety of topics related to the course content. The modules, which counted as extra credit for the students, were created by Brinn McDowell (graduate assistant) and Jan Hu (undergraduate assistant) with review from Dr. Matt Wise (course instructor). In addition to the modules, two surveys - one at the beginning and one at the end of the semester - were released to not only gauge the student participants’ knowledge on green chemistry topics, but allow them to voice their opinion on the pilot effort.

Overall, the pilot has proven to be a successful example of integration of green chemistry into an existing chemistry course using a method that not only is cost-effective and bolsters student opportunity for leadership but takes into consideration time-constraints of instructors. The following items are an indication of that success:

- Results collected during the pilot demonstrate that student participants not only learned and stayed engaged in the material, but found green chemistry to be effective in helping them to apply real life scenarios to the original course content. The majority of students also indicated the value that green chemistry knowledge can add to their future careers.

- The student Teaching Assistants (TAs) found that writing the course curriculum offered them a unique professional-development, leadership opportunity that enhanced their resume.
- The course instructor found that utilizing TAs to work to integrate green chemistry into the introductory chemistry lecture material was a time- and cost-effective solution for instructors. Hiring TA's to provide support in curriculum development allowed the instructor to stay focused on the course while still providing an opportunity to supplement that course content with green chemistry principles and knowledge.
- As of the Fall 2022 semester, the 10 green chemistry modules are now fully integrated into the point structure of the CHEM 1021 introductory chemistry course at CU Boulder.

Next steps would be to integrate green chemistry content into additional chemistry courses at CU Boulder utilizing the pilot methodology. The Chemistry Department is supportive of moving in this direction but there is a need for funding to hire additional teaching assistants to make that a reality. In the meantime, efforts are being made on a limited basis to begin to integrate green chemistry content into some recitations for General Chemistry 2 - CHEM 1133. Progress will be slow at CU Boulder until needed support is provided.

1 Introduction

From the chair you're sitting on to the food you ate for lunch, chemicals make up the world around us. Every physical substance is made up of the components of matter: elements, compounds, and molecules. Now, constantly being exposed to chemicals often brings to mind a negative connotation; however, it doesn't have to be that way. This is where Green Chemistry comes in. Green chemistry applies across a chemical product's life cycle from design to disposal. Ultimately, still providing the benefits of chemistry while eliminating toxic exposure and pollution at its source. The Environmental Protection Agency (EPA) defines green chemistry as "the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances" (EPA, 2022).

Green chemistry is a fairly new field getting its roots in the Pollution Prevention Act of 1990. Stopping the creation of pollution at the source became policy instead of just through treatment and disposal. Throughout the decade, the EPA's Office of Pollution Prevention and Toxics launched a grant program to encourage the redesign of existing hazardous chemicals and then in partnership with NSF started early green chemistry research. In 1996 the Presidential Green Chemistry Challenge Award was created, which helped to gain national attention. In 1998, the 12 Principles of Green Chemistry created by Paul Anastas and John Warner were published, and further helped to set guidelines for this emerging field. Over the past two decades, the field has continued to grow (EPA, 2022).

With increasing demand for the implementation of green chemistry, organizations, industry, and education institutions alike have been working towards adequately training the potential workforce in this knowledge base. Some of the pioneers in this space include Beyond Benign, American Chemical Society, and higher education institutions including Yale UNIDO, University of California Berkeley, Colorado School of Mines, George Washington University, UMass Boston, and University of Oregon. Furthermore, a policy statement put out by the Green Chemistry and Commerce Council signed by companies such as Johnson and Johnson, Dow Chemicals, and 31 other companies called on higher education to "integrate green chemistry and sustainability principles into chemistry, engineering, science and business curricula" (GC3). Another show of support for green chemistry came from the National Science Foundation (NSF), a major funding source for chemistry research. The NSF wrote a letter calling on colleagues to include sustainable chemistry into their proposals and projects (NSF, 2022).

2 Background

The push for green chemistry knowledge is not only coming from organizations outside of the University of Colorado Boulder (CU Boulder), but also has been a point of interest by the CU Boulder Green Labs Program, members of the CU Boulder Chemistry Department, and CU Boulder students. CU Boulder is already a leader in sustainability and in many regards with green chemistry principles as well, implementing numerous actions to promote more sustainable lab practices that other universities have yet to begin (including a solvent reuse program, recycling of chemical glass bottles and metal drums, and replacement of teaching lab experiments with green chemistry experiments). In regards to green chemistry education, a continuous survey effort of student interest in green chemistry has been run, which resulted in a white paper written by Natalie Kra and helped to create this pilot. Additionally, CU Green Labs in collaboration with CHEMunity (a CU Boulder graduate chemistry student group) created the CU Boulder Green Chemistry Certificate Scholarship Program in 2018 enabling a small number of CU Boulder students to participate in an online green chemistry certificate program at the University of Washington. While these actions represent progress for green chemistry at CU Boulder, incorporating green chemistry into the chemistry lecture curriculum has been noted as a point of improvement that would enable thousands of students per year exposure to green chemistry as they pass through the introductory, general, and organic chemistry courses required by a wide range of majors.

2.1 Previous Survey Effort at CU Boulder

The CU Boulder Green Labs Program in collaboration with the CU Boulder chemistry department has conducted a survey of student interest for including green chemistry education into the chemistry curriculum. The survey was run on CU Boulder's Qualtrics platform and distributed to students in the Fall of 2018, Spring of 2019, and Fall of 2021. It reached 302, 225, and 240 students respectively. The survey was sent to students of varying majors taking courses in introductory, general, and organic chemistry (Figure 1). The most represented major in the surveys has been biology with participation from 116 students in biological majors in the most recent distribution of the survey. However, the surveys have reached students in business, environmental science, psychology and neuroscience, chemistry, math, and computer science, and engineering as well as others (Figure 2). The course with the most representation from chemistry majors was CHEM 1133 with 6 students answering the survey (Figure 1). Although there has been some variability in the courses that have participated from semester to semester, the questions concerning student interest in green chemistry education have remained constant over all distributions to help keep consistency in the data collected.

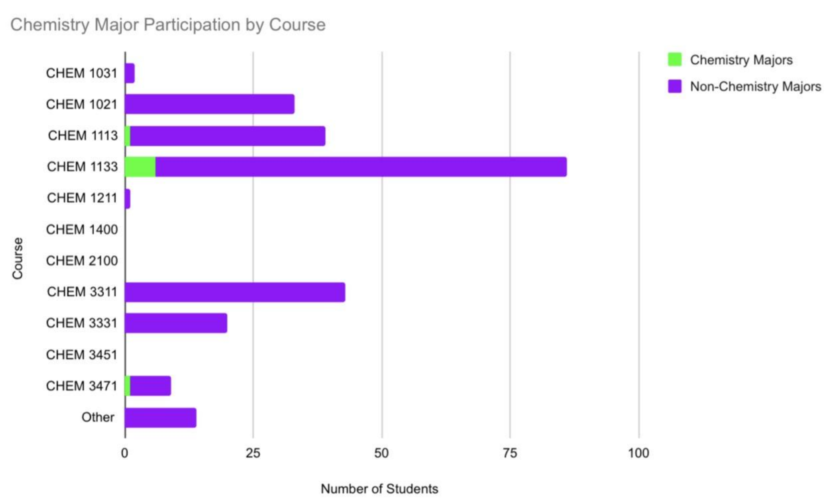

Figure 1. Participation in 2021 survey effort by course and by chemistry major vs. non-chemistry major.

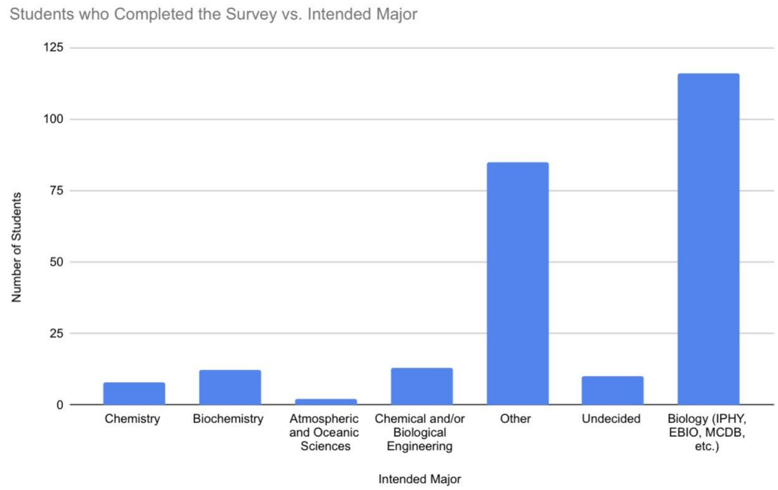

Figure 2. Student participation in the 2021 survey efforts by their intended major.

This most recent survey was sent to students from November 29th, 2021 - December 15th, 2021. This time frame was chosen to allow students to reflect on their course over the past semester, and provide feedback on their current exposure to green chemistry principles in addition to gauging their interest in the topic. The chemistry department, Biochemistry and Chemistry Club ([(B)chem club]), and CU Green Labs worked together to promote the survey to students by having instructors distribute the survey link to students on Canvas, chalking the board of general chemistry teaching labs with reminders, posting on social media platforms, and having students post the link for the survey in chemistry class zoom chats. It was assumed that the only students who completed the survey were taking chemistry lecture courses, and answered the survey questions to the best of their ability. The data collected from the survey was then synthesized by question on the qualtrics platform. Six of the surveys were discarded due to being incomplete. The data from the past surveys were then compared against each other to allow for analysis of trends.

The Fall 2021 Green Chemistry Student Survey revealed that students have a strong desire to learn more about green chemistry. **Of the 240 students that participated in the survey, 86% were very interested, interested, or a little interested in learning more about green chemistry.** In their courses, 48% of students reported that green chemistry was never mentioned, and 28% of the students selected that green chemistry was talked about once in the semester. The survey asked if students in addition to being interested in the topic would have liked to see more green chemistry topics mentioned in their courses and 81% replied: “yes”. **When students were asked if they could choose between taking their current course or their current course with a green chemistry emphasis, 69% of students expressed that they would choose the course with a green chemistry emphasis.** These results display that not only are students curious about green chemistry principles but want them to be included in the chemistry curriculum.

The three surveys have shown that not only do a majority of students want some green chemistry education, but also that percentage continues to increase from year to year. The most supported scenario by students for green chemistry education was to implement green chemistry principles into the current curriculum and courses being taken. All three surveys have also displayed that, as this topic gains awareness, students gain interest in wanting to explore the topic of green chemistry further. More information on all three surveys can be found on the CU Green Labs website.

3 Project Objectives

In response to the interest displayed by CU Boulder students in each of the three previous survey efforts, the Director of Chemistry Instruction and Associate Chair for Undergraduate Academic Affairs, Matthew Wise, PhD., in collaboration with CU Green Labs piloted a methodology during the spring semester of 2022 to integrate green chemistry content into an existing chemistry lecture course.. The object of this pilot was to:

- Integrate green chemistry concepts and content into the 10 syllabus units covered by the CHEM 1021 course
- Test the ability of student teaching assistants to create meaningful green chemistry course content.
- Expose CHEM 1021 students to green chemistry concepts and measure the impact.
- Determine the effectiveness of this methodology for integration of green chemistry into existing CU Boulder chemistry course lecture curriculum.

4 Methodology

The course, Introductory Chemistry- CHEM 1021, was chosen as the pilot course because it reached 217 students of varying majors, the laboratory and lecture portions of the course were integrated into one section encouraging easier adaptation to the course material, and there was one professor for the course, which avoided variation between instructors' teaching styles and content.

The pilot began with a review of existing education material (green chemistry and introductory chemistry), creation of a scope and measurements of success, and decisions of how green chemistry topics can align with CHEM 1021 course topics. The pilot consisted of 10 green chemistry focused modules in the form of quizzes, each with 10 questions, that explored a variety of topics and related them to course content. The modules were created by Brinn McDowell (graduate assistant) and Jan Hu (undergraduate assistant) with review from Dr. Matt Wise (course instructor). Due to a lack of time in the semester, the 10th module that was created was not distributed to students. This resulted in nine modules being shared with students and used for data collection.The 10 modules can be viewed in the appendix to this white paper.

The 10 module topics were:

- What is green chemistry and why is it important?
- 12 principles of green chemistry

- Periodic Table, Groups in PT, Ionization Energy, Electronegativity
- How UV light affects cells and planet
- Sustainability and Life Cycle Assessment
- Solvents, their role and working without them
- Catalysis, Designing for Recycling and Degradation
- Stoichiometry and Reactions
- Green Chemistry and Energy
- The Molecule

The first nine modules were released individually on the course Canvas page after the completion of each lecture topic slide deck. They remained open with no time limit for a week after release, and counted as extra credit towards the student's grades. In addition to the modules, two surveys at the beginning and end of the semester were released to not only gauge the student participants' knowledge on green chemistry topics, but allow them to voice their opinion on the pilot effort.

Success of the the pilot was measured through a few indicators
- The student surveys at the beginning and the end of the semester for their familiarity and interest in green chemistry topics.
- The 10th question on modules 2-9 that measured the student's opinion on the effectiveness of the individual modules on a numerical scale.
- The view of the course instructor on the convenience and economics of having student teaching assistants help support curriculum development.
- The view of the student teaching assistants of the professional development opportunities gained through this experience.

5 Discussion

Students, teaching assistants, and the course instructor all found the pilot effort to be successful in the goals that it intended to achieve. Before the pilot, students in CHEM 1021 reported that they had very little previous exposure to green chemistry within their education. They also reported that they had high interest in learning about these topics. After the pilot effort, not only did they show interest in a continuation of learning green chemistry in future courses, but also that they found it helpful with their learning of the standard course material, and saw it as beneficial knowledge to their future careers. The teaching assistants found that the creation of course material provided a unique professional development opportunity, and communicated that it has helped them to gain skills applicable to their future career goals. Furthermore, the course instructor reported that the modules helped students to connect course topics with real world applications.

5.1 Student Perspective

The student perspective of the pilot was gauged through individual module results, and surveys at the beginning and end of the semester.

5.1.1 Individual Module Results

The effectiveness of the modules as a whole was monitored by tracking the average score of each module, the completion rate per module, and the effectiveness of each module in implementing green chemistry topics into the course curriculum as reported by students. The average score per module (where score is the percentage of correct answers to the quiz questions) was evaluated to help the teaching assistants understand the level of difficulty (Figure 3). The goal was to have an average score of around 80%. Module 6 had the lowest overall average score of 62%.

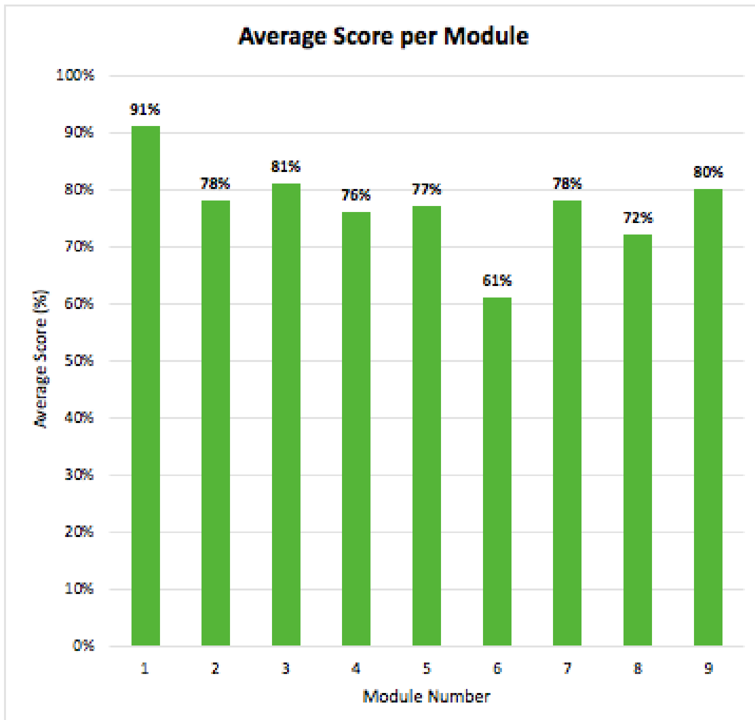

Figure 3. Average percentage of correct answers (a.k.a. average score) per module

Additionally, the completion rate for each module was collected to understand the percentage of students from the class that participated in each module. The modules were incentivized as extra credit toward student grades, and were voluntary to complete. Despite the modules being voluntary, the average completion rate within the class was 52%. The highest level of participation was in module 1, and the lowest level of participation was in module 5 (Figure 4). The factors affecting the completion rate were not explored further.

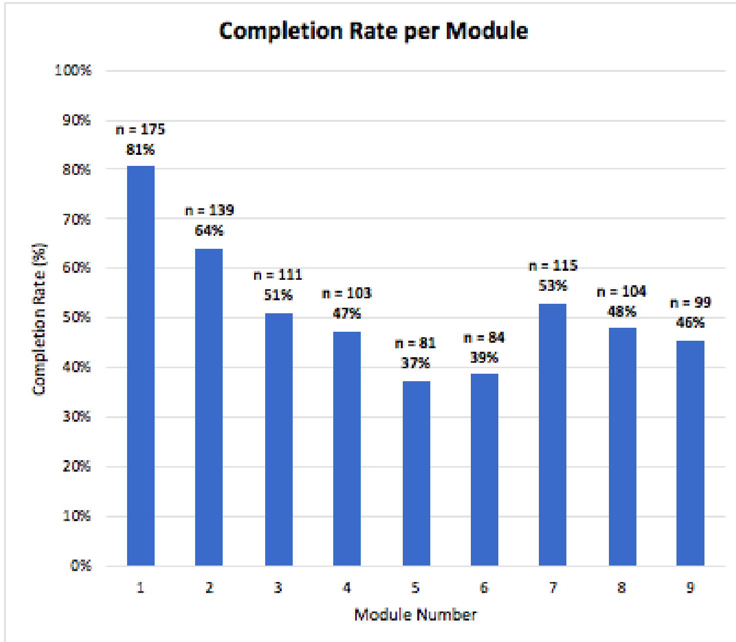

Figure 4. Average completion rate per module for a class of 240 students

Students also had the opportunity to provide feedback on each of the modules ranking whether they felt that the individual topic area was effective in implementing the topics of green chemistry in CHEM 1021. For every module, the majority of students reported that the modules were somewhat effective, effective, or very effective in their delivery of information (Figure 5). This information was used to gauge the quality of the materials created.

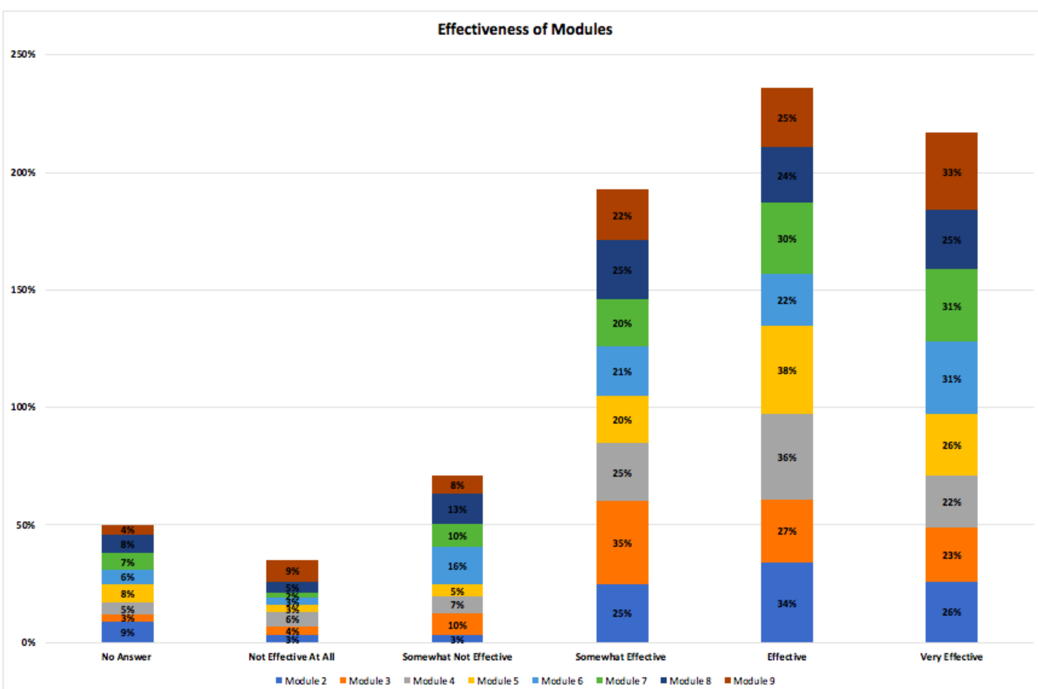

Figure 5. Effectiveness of modules as reported by students

5.1.2 Beginning of Semester Survey Results

The beginning of the semester survey was an initial assessment of the students' previous knowledge, and interest pertaining to green chemistry in their education. When asked about exposure to green chemistry topics, 83% of the student respondents reported that they had no former exposure before this course. As a follow up question, the students were asked about their interest level in learning about green chemistry principles. The survey revealed that the majority of respondents were interested or very interested in learning about Green Chemistry (Table 1).[1]

How interested are you in learning about green chemistry principles? (n = 152)	
	Number of Respondents
Very interested	40
Interested	71
Moderately Interested	52
Not at all interested	2
No answer	8

Table 1. Student interest in learning green chemistry principles[1]

5.1.3 End of Semester Survey Results

At the completion of the pilot, a similar survey was conducted to gauge the success of the modules incorporating green chemistry into the CHEM 1021 course. Success was evaluated through respondents' interest in seeing green chemistry topics implemented into future courses, and how it affected their experience within CHEM 1021. In response to being asked if they would like to see a continuation of green chemistry being implemented into future courses the majority of students reported in support of future course exposure (Table 2)[2]. In regard to the students' perspective of the green chemistry within the course, 53% of participants reported that they found the module helpful in connecting real-life applications to the topics learned in the course. Additionally, nearly 25% of the respondents found themselves applying green chemistry topics to the lab portion of the course.

[1] The students were allowed to choose more than one answer resulting in double counting of the participants.
[2] Please refer to footnote 1

Would you like to see green chemsitry education incorporated into your future chemistry courses? (n = 36)	
	Number of Respondents
Yes, in the same format as this semester	21
Yes, but in a different format than this semester	8
No	1
N/A (not taking another chemitry course)	7
No answer	9

Table 2. Student interest in seeing green chemistry in future chemistry courses[2]

The end of the semester survey also asked students if they thought green chemistry knowledge would be advantageous with their career path. The majority of students responded that, after the modules, they felt that learning green chemistry was beneficial to their future careers (Table 3)[3].

Do you feel that green chemistry knowledge would be beneficial to you future career path? (n = 36)	
	Number of Respondents
Yes	17
Somewhat	15
No	8
No Answer	9

Table 3. Student perception of green chemistry knowledge and its benefit to their future careers[3]

When asked about strengths and weaknesses of the pilot as a whole, the student respondents noted that an area of improvement was how the information was delivered within the modules. They suggested that videos helped to enforce topics over supplemental readings. Some areas that proved effective for the students were the overall length of the modules, the topic areas covered, and the use of extra credit as an incentive.

5.2 Teaching Assistant Perspective

When asked to provide feedback on the pilot, and how writing the curriculum supported professional development, **student teaching assistant and Chemistry major Jan Hu said**,

"[Today] My work primarily concerns the scalability of processes within the textile industry, one of the main polluters of clean water in the world. My unique opportunity to develop a green chemistry pilot last year allowed me to assess and address these environmental & safety concerns within my work post graduation. My background in Green Chemistry has also given

[3] Please refer to footnote 1

my work perspective and makes my day to day more exciting as I know my work has a far reaching impact for the betterment of the environment!"

5.3 Course Instructor and CU Green Labs Perspective

Matt Wise Ph.D., CHEM 1021 Spring 2022 Course Instructor:
The course instructor (Matt Wise Ph.D.) for CHEM 1021 viewed this pilot as a success because the modules not only added value to the students' learning, and were done in a way that was mindful of his time as an instructor with an already busy schedule. Matt Wise Ph.D. stated,

"A main complaint about CHEM 1021 [from previous students] is that students don't understand how introductory chemistry concepts relate to real world applications. The quizzes were instrumental in helping students understand how chemistry can be applied to real world scenarios which better the environment we live in."

Kathryn Ramirez-Aguilar, PhD, Manager of the CU Boulder Green Labs Program:
"The success of this pilot opens the doors to utilize this same methodology to integrate green chemistry into additional chemistry courses at CU Boulder and could even serve as a methodology for incorporation of sustainability into other science courses beyond chemistry. Importantly, the pilot methodology helps overcome one of the largest hurdles I have witnessed for moving such curriculum projects forward, the limited time of instructors with busy schedules to develop green chemistry or sustainability content. Through use of student teaching assistants (TAs) with the appropriate knowledge and expertise, course materials can be created while only requiring the time of instructors to provide guidance and to review and revise where needed the materials created by the TAs. The research and draft course material creation can be accomplished by the TAs, saving the instructors significant time. Furthermore, the use of student TAs is a cost-effective approach that also provides student TAs with a real-world, resume-building, learning opportunity that involves the applied use of their education. This can only benefit their employability once leaving CU Boulder.

I would also like to comment on a couple of important positive impacts of this pilot and of expanding this pilot to additional chemistry courses. Since many different majors require chemistry courses, the integration of green chemistry into chemistry classes (such as introductory, general and organic chemistry) provides the opportunity to educate and expose students in a diverse set of majors to green chemistry principles, students that will enter into many different fields of work. Thus, the reach and lasting impacts of this project are far and wide. Another important aspect of green chemistry education is that it not only benefits environmental sustainability but also environmental justice. The words of a previous CU Green Labs student assistant and CU Boulder Business School and MENV graduate student, Natalie Kra, sums this up well, "When students practice green chemistry, they learn to think critically about the global and environmental impact of their field and the possibility of an environmentally just future for all people regardless of socio-economic stature. The benefits of moving in this direction are tremendous - not only for the students but also for the university as a whole and its role in preparing students to be responsible citizens of the world. If we can teach the next generation to design products to be non-toxic from the start of their lifecycle and to design manufacturing to minimize waste that is harmful, our very own students can help to minimize the issue of exposing populations of people to the harmful conditions associated with modern production processes. Green chemistry is about finding alternatives to many of these harmful processes that often disproportionately impact communities of color, so this subject supports justice, equity, diversity, and inclusion (JEDI) efforts of the university. By making the connection between environmental issues and racism, students can learn to think critically about the societies in which they live and work, better positioning them to become leaders in their communities."

6 Conclusions

Students, teaching assistants, and the course instructor found this to be a successful way to implement green chemistry into higher education curricula. The majority of 1021 students who participated found the modules to be effective in teaching green chemistry topics that could be beneficial to their future careers. Additionally, by releasing the modules through Canvas, the modules were added to the curriculum with limited interference to classroom instruction, and without a significant burden to the course instructor's already busy schedule. This pilot demonstrated that student teaching assistants educated in chemistry can create meaningful curriculum in a way that is cost-effective for universities and beneficial to the teaching assistant's and students' professional development alike.

The green chemistry modules created for Introductory Chemistry (CHEM 1021) have continued to be used and improved within the Fall 2022 semester and intentions are to continue their use into the future. Instead of being extra credit, they are now integrated into the point grading structure of the CHEM 1021 course. Furthermore, efforts have expanded to include a version of implementation in General Chemistry 2 (CHEM 1133) within recitations. However, in order to continue to expand into other chemistry courses, funding is needed to hire teaching assistants to not only create content for the additional chemistry classes but also for continual improvement of the modules. This latter point is critical in making sure the student receives the best possible green chemistry education.

7 Appendix

A compilation of all of the modules can be found in the Supplemental Materials document.

8 Resources

Basics of green chemistry. (2022, May 17). US EPA.
https://www.epa.gov/greenchemistry/basics-green-chemistry

Dear colleague letter: Critical aspects of sustainability (CAS): Innovative solutions to sustainable chemistry (CAS-SC) (nsf22111) | NSF. (n.d.). NSF - National Science Foundation.
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