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Development of an Introduction to Sustainable Engineering Course as a Chemical Engineering Elective

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Abstract

Due to the pressing global challenges of climate change, resource depletion, and environmental degradation, there is a growing need for sustainable engineering education. In response to student interest and employer requests, an Introduction to Sustainable Engineering course has been developed in the Ralph E. Martin Department of Chemical Engineering at the University of Arkansas. The class has been structured as a three credit-hour elective for upper-level undergraduate and graduate students. The course has been taught for two semesters, and it has been approved to count toward the university-level minor in Sustainability. As an introductory course, it exposes students to a broad range of topics in the field and prepares them for subsequent sustainability courses. An emphasis is placed on real-world applications across the three pillars of sustainability through interdisciplinary collaboration, industry speakers, and case studies. Key components of the course include foundational sustainability principles, corporate environmental, social, and governance (ESG) reporting, decarbonization, sustainability in materials, life cycle assessment (LCA), renewable energy, and sustainable engineering design principles. In addition, students participate in three lab components—two experiments and one demonstration—exploring alternative energy sources including the production of H_2 fuel, solar power, and polymer pyrolysis to fuel oil. Student learning is assessed through reflection papers at the end of each unit, two lab reports, and a group project at the end of the semester. A new course in LCA will be taught in the department in Spring 2024 to supplement the sustainability curriculum.

The Introduction to Sustainable Engineering course was offered first in Spring 2022 and again in Fall 2023. At the beginning of the Fall 2023 course, a pre-assessment was administered to the students to establish a baseline of knowledge. At the conclusion of the semester, a post-assessment measured student growth in their understanding of sustainability concepts. Students completing the course should be able to explain the principles and concepts that underlie sustainability, including environmental, social, and economic aspects. Furthermore, the students should be able to develop sustainable solutions to real-world problems involving the chemical industry and chemical engineering applications. This paper describes the course outline, assessment mechanism, lab components, and results from the pre- and post-assessments. Lessons learned and future improvements for the course are also discussed.

Keywords

sustainable engineering, engineering education, course development, sustainable materials, engineering elective, chemical engineering, laboratory experiments

Introduction

Programs in sustainability have been on the rise in U.S. universities over the last two decades. The Association for the Advancement of Sustainability in Higher Education (AASHE), founded in 2004, states that there are now 756 institutions of higher education in 31 countries that have developed 4,086 programs in sustainability [1]. Nearly 500 sustainability programs have been developed worldwide in engineering alone. As might be expected, the programs differ significantly by discipline and methods of instruction. A few examples from the engineering literature include the addition of sustainability projects in multiple classes throughout the curriculum at several universities [2, 3], the introduction of sustainability modules in multiple industrial engineering courses at the University of Texas at Arlington [4], a natural resources approach to teaching sustainability to general engineering students at Dartmouth [5], an environmental engineering sustainability course at Oklahoma State University that focuses on international standards [6], a first-year sustainability studies course at Rensselaer Polytechnic Institute [7] and a four-semester earth sustainability-themed general education curriculum developed at Virginia Tech University [8]. Within the chemical engineering discipline, the American Institute of Chemical Engineers (AIChE) lists 218 institutions as having an undergraduate sustainability program [9].

This paper focuses on the development of an engineering sustainability course in chemical engineering at the University of Arkansas. Mitchell and Carew [10] noted that even third-year chemical engineering students have different ideas on what sustainability means, with their ideas ranging from naïve to sophisticated.

Overview of the Course

In response to student interest and employer and alumni requests, it was decided that an Introduction to Sustainable Engineering course should be developed in the Ralph E. Martin Department of Chemical Engineering at the University of Arkansas (U of A). Prior to Spring 2022, there were no courses within the chemical engineering curriculum that counted toward the university-level minor in Sustainability at the U of A. This meant that students minoring in Sustainability were required to take additional courses outside the chemical engineering department and potentially add to their required degree credit hours.

Once it was determined that a sustainability course would be developed, an initial review of chemical engineering programs revealed that that there were not many broad-based Introduction to Sustainability courses that presented the principles of sustainability across all three pillars—environmental, social, and economic—in a chemical engineering context. In addition, few sustainability textbooks or academic resources were found which were geared toward the chemical engineering industry. As a result, it was decided that materials for this introductory course would be compiled from various resources while leveraging guest speakers working in the field.

In Spring 2022, the Introduction to Sustainable Engineering course was offered as a three credit-hour upper-level undergraduate elective and graduate elective course. As an introductory course, the goal was to expose students to a broad range of topics in the field as it pertains to engineering and to prepare them for subsequent courses in sustainability. The course emphasized real-world applications across the three pillars of sustainability through interdisciplinary collaboration, industry speakers and case studies. Twenty undergraduate chemical engineering students registered for the course, filling it to capacity on the first day of registration. The course enrollment was intentionally kept small to support focused class discussions. During the semester, there were six guest speakers from industry who spoke on topics such as LCA and sustainable procurement in the chemical engineering industry. In addition, the students visited a plastic recycling plant and a local business with awarded sustainability efforts and training. Several LCA case studies were discussed throughout the semester. As the final project, students worked in groups to perform and present an LCA study using OpenLCA software. Student feedback at the end of the course showed that the course was well-received (*"Overall, I would rate this course as:"* 4.60/5.0), and the students appreciated the discussion-based learning and experiential components. Two of the 20 students accepted jobs in sustainability-related fields upon graduation. Some suggestions for future courses were to have fewer guest speakers and more quantitative analysis in the course to balance the conceptual learning.

In 2023, the Ralph E. Martin Department of Chemical Engineering received a Biggadike Innovation Grant for the establishment of an engineering sustainability focus area in the department. The purpose was to strengthen the current Introduction to Sustainable Engineering course by developing lab components which allowed application of course material, as well as to develop other courses that would include a focus in engineering sustainability. Since then, two courses supported by the grant, Introduction to Sustainable Engineering and LCA courses, have been provisionally accepted as electives for the U of A minor in Sustainability.

In Fall 2023, the Introduction to Sustainable Engineering course was offered for a second time. Registration was expanded to 22 undergraduate and five graduate students. In this second offering, the course was augmented to include three lab components—two experiments and one demonstration—exploring alternative energy sources including the production of H_2 fuel, solar power, and polymer pyrolysis to fuel oil. Other experiential learning units included a personal carbon footprint study, a waste minimization challenge and a visit to a plastics recycling plant. Case studies discussed throughout the semester included scope 1-3 emissions, an interdisciplinary solar project, and LCA. By this time, a separate LCA course was being developed, so that topic was less of a focus in this offering of the introductory course. For the final project, students worked in teams to develop a report and presentation covering sustainability issues within a particular sector of the chemical engineering industry of their choice, considering the social, economic and environmental impacts. Again, student evaluations indicated that the course was well-received (*"Overall, I would rate this course as:"* 4.47/5.0). Pre- and post-assessments showed growth in the students' familiarity with concepts of sustainability, particularly for applications within the field of chemical engineering.

Development of Course Topics

As the first sustainability focused course in the Ralph E. Martin Department of Chemical Engineering at the University of Arkansas, it was important to assess the students' previous exposure to the topic. A survey revealed that the 20 students first taking the class in Fall 2022 had knowledge of sustainability through the following methods:

- One student was minoring in sustainability
- Three students had performed research involving biofuels
- Four students had interned for companies focused on the environment or fuels
- Four students were involved with sustainability clubs on campus
- Five students had taken classes that focused on sustainability, either completely or in part

However, through class discussion, it became clear that the students' understanding of sustainability was primarily focused on the environment and energy. Very few of them had any connection of the topic to economic or social aspects. As a result, it was determined that the first few weeks of the course needed to cover foundational topics in sustainability, including the interconnectedness of the three pillars (environment, social, economic).

A list of general topics from Spring 2022 is shown in Table 1. Based on industry and student feedback, adjustments were made to the course topics for the next course offering in Fall 2023. The course still provided broad exposure to the field, but the focus was narrowed to process engineering areas of impact. These included energy sources and usage, decarbonization, waste minimization, materials, and sustainable design. The course topic list for Fall 2023 is presented in Table 2. Some of the topics were addressed over multiple class periods. Course content was tied to real-world applications through industry speakers, site visits and case studies. In addition to these topics, the Fall 2023 course also incorporated lab experiments and other forms of experiential learning. These are described in the next section.

Table 1. General Topics Covered in Introduction to Sustainable Engineering – Spring 2022

Weeks	Unit	Topic
1-3	1	Introduction of Sustainability Concepts
4-6	2	Corporate Sustainability Practices
6-9	3	Sustainable Materials
10-12	4	Sustainable Energy Systems
13-14	5	Sustainable Engineering Design Principles
15-16	6	Final Project Presentations

Table 2. Course Topics in Introduction to Sustainable Engineering – Fall 2023

Weeks	Unit	Topic
1-2	1	Sustainability, as defined by the Brundtland Report
		The Three Pillars of Sustainability
		The UN Sustainable Development Goals
3-5	2	Greenhouse Gases
		Climate Change
		Net Zero Goals
		Science-Based Targets Initiatives
		Scope 1-3 Emissions
6-7	3	Carbon Footprint Calculation & Mitigation
		Decarbonization Strategies
8-9	4	Developing Sustainable Materials
		Plastics & Biodegradable Plastics
		Mechanical and Chemical Recycling of Plastics
		Waste Minimization
10-11	5	Life Cycle Assessment

		Corporate ESG Reporting
12-13	6	Overview of Alternative Energy
		Electrification of Transportation
14-15	7	Green Chemistry
		The12 Principles of Sustainable Engineering Design
16	8	Final Project Presentations

Laboratory Experiments

With the support of a Biggadike Innovation Grant, laboratory experiments were developed to augment the course content in the initial Introduction to Sustainable Engineering course. These laboratory experiments investigated aspects of hydrogen production and solar energy. In addition, a waste plastics pyrolysis to fuel demonstration, carbon footprint study, zero waste challenge, and site visits provided additional experiential learning opportunities.

H_2 Production Laboratory Experiment

In the H_2 production laboratory experiment, students produced hydrogen from water via electrolysis using a polymer electrolyte membrane (PEM) hydrolyzer, shown in Figure 1.

Figure 1. Hydrogen Production using a PEM Hydrolyzer

The purpose of this laboratory experiment was to:

- Demonstrate the production of hydrogen and oxygen from water using a laboratory PEM hydrolyzer
- Determine the effects of power and membrane area on the hydrogen production rate and the ratio of H_2/O_2
- Do preliminary calculations on the cost of producing hydrogen from water

The cost analysis was to be compared to the U.S. Department of Energy goal for the cost of hydrogen production by electrolysis of $2 per kg of H_2 by 2025 and $1 per kg of H_2 by 2030 [11]. The students showed that the cost of power for the laboratory unit was about $4-5 per kg of H_2, which is significantly higher than the 2025 DOE target of $2 per kg of H_2.

The hydrolysis lab led to a vibrant class discussion which focused on the importance of balancing the environmental and economic pillars of sustainability. The discussion also highlighted the complexity of switching to alternative energy sources. Students rated the electrolysis lab 4.07 out of 5 for contributing to learning.

Solar Panel Laboratory Experiment

In the Solar Panel laboratory experiment, students used small solar panels to collect energy from an overhead light source. The solar panel could be positioned orthogonally to the light source or adjusted to simulate a typical roof pitch. The movement of the light source from left to right over the stationary panel simulated the movement of the earth relative to the sun. The experiment demonstrated how light is collected with solar panels and used to generate electricity, while also demonstrating the efficiency of typical collectors. Figure 2 shows the experimental set-up for collecting light using solar panels.

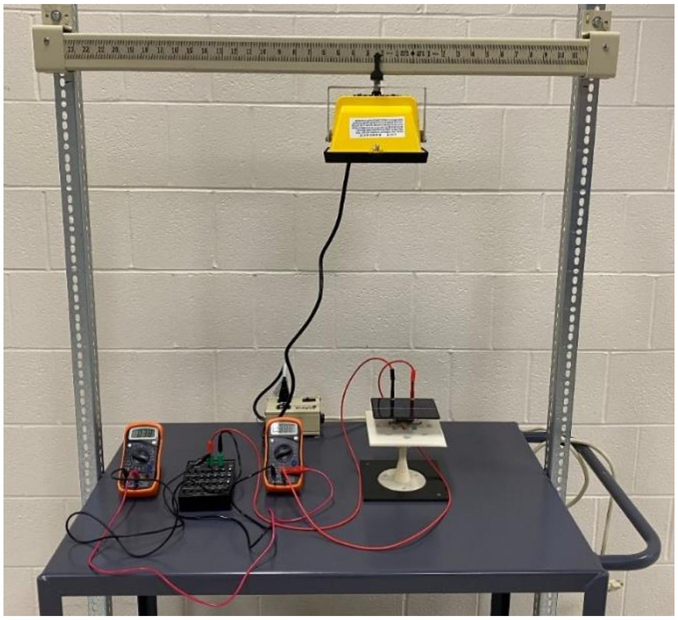

Figure 2. Experimental Set-up for Collecting Light using a solar panel

The purpose of this lab experiment was to:

- Demonstrate the use of a solar panel in converting light to power
- Investigate the effects of panel orientation (relative to the source) for a stationary panel in maximizing the daily power that could be collected as electricity
- Determine the efficiency of a small solar panel in converting light to energy

The students demonstrated that proper orientation of the solar panels is essential to maximize energy production. The flat (orthogonal) placement generated significantly more power than the pitched placement. The efficiency in collecting light using the small, flat plate collectors ranged from 3-6%, depending on the position of the light source, while the collection efficiency from the pitched plate ranged from 1-2%. Students rated the solar panel efficiency lab 4.19 out of 5 for contributing to learning. In future semesters, the solar panel lab could be extended to include a financial analysis that includes purchase price of the panels, tax credits, and a return-on-investment calculation.

Plastics Pyrolysis to Fuel Demonstration

In consultation with Willie (Skip) Rochefort, a professor at Oregon State, a laboratory-scale pyrolysis reactor was constructed to demonstrate and study the pyrolysis of waste plastic to produce usable liquid fuel. The pyrolysis unit, shown in Figure 3, is capable of handling 1 kg of waste plastic and operates at a temperature of 500 °C under an inert nitrogen atmosphere. The typical heat-up time for the reactor is about 3 hours and the residence time after heat-up is 3 hours. Due to time constraints, students weren't asked to run the experiment. The pyrolysis reactor was demonstrated, showing samples of the source waste plastic and the product oil, which consists primarily of alkanes and less than 10% alkenes. The yields of products from low-density polyethylene (LDPE) and high-density polyethylene (HDPE) are identical at 77% liquid fuel oil, 22% non-condensable gases, and 1% char.

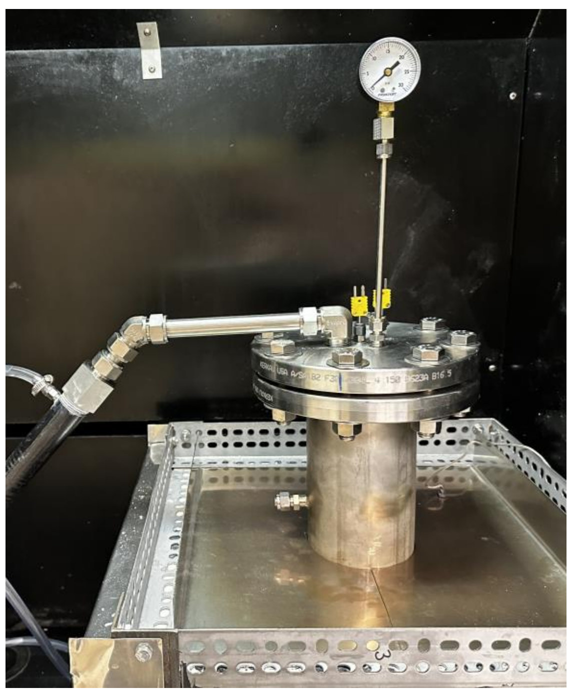

Figure 3. Laboratory Pyrolysis Reactor for Converting Waste Plastic to Liquid Fuel

Carbon Footprint Study

Each student completed a personal carbon footprint analysis using an online climate calculator developed by Climate Hero [12]. This online program was chosen for its ease of use and short time of completion, less than five minutes on average, which allowed sufficient time for a follow-up class discussion. The purpose of this activity was for students to understand the impact of their personal lifestyle decisions on the global climate.

In the analysis, the questions focused on the person's home, travel and consumption habits. A carbon footprint is then calculated and reported in CO_2 equivalence (ton eCO_2/yr). Personal carbon footprints are shown compared to the global average carbon footprint and reduction strategies are suggested. The program provides the opportunity to offset carbon emissions to net zero through the purchase of carbon offsets and sponsorship of global climate projects. This led to an engaging class discussion about consumer habits, carbon offsets, carbon taxes and socio-economic considerations. The discussion was then expanded to include corporate carbon footprint and global climate responsibility.

Zero Waste Challenge

During the waste management unit, the students were given an opportunity to voluntarily participate in a zero-waste challenge competition. The students were given clear plastic bags and asked to collect any waste that could not be diverted from a landfill for a week. The purpose of the exercise was to increase the students' awareness of waste habits and the impact of lifestyle choices in their waste production. At the conclusion of the week, the collected waste was weighed, sorted by type and discussed. The United States Environmental Protection Agency (EPA) reports that the average person in the United States generates 4.9 pounds of municipal solid waste per day [13]. Of the students who participated in the waste challenge, all of them produced less than the national average of waste. However, it was noted that the week wasn't typical because they were focused on reducing their waste.

Besides the amount of waste, the students also observed other trends that resulted from the challenge. The most common waste came from food packaging. Whether the food was from a grocery store, restaurant or drive-through, it was almost impossible to buy food without packaging. Another observation is that students who had children in the home collected much more waste. International students generated less waste than domestic students. The students also noted the impact of having convenient access to recycling opportunities. Curbside recycling and recycling bins throughout the campus and community greatly increased their likelihood of use.

Site Visits

The class visited the Fayetteville Recycling Facility. The facility sorts what is collected from the curbside recycling program and then packages the material to sell as feedstock to companies (see Figure 4). Students learned about the types of material (glass, plastic, metal and paperboard) that are recycled and the economics of each process. The environmental educator explained the pay-as-you-go recycling system and emphasized the need for the recycling program to be financially independent. The selling price and production cost of each feedstock was given, and students learned that the city makes the most profit from the sale of used cardboard.

Figure 4. Bales of Collected Plastic and Metal at the Fayetteville Recycling Facility

Assignments

The Introduction to Sustainable Engineering course was developed so that learning would be driven by class discussions and individual student interest. Attendance and class participation were paramount and contributed a portion of the course grade. At the end of each learning unit (every 2-3 weeks), students submitted a written peer review essay related to the material covered in that unit. The peer review essay was to be from an approved book chapter, journal or technical article, YouTube video, podcast or movie. Students were expected to vary the media to broaden their exposure to sustainability resources. Students also submitted two lab reports for the H_2 Production and Solar Panel laboratory experiments.

For the final project, students worked in teams to develop a report and presentation covering sustainability issues within a particular sector of the chemical engineering industry of their choice, considering the social, economic and environmental impacts. Some examples of the final project topics include the pharmaceutical industry, the textile industry, metal manufacturing and rail transportation. Graduate students in the course were to prepare a report and presentation covering sustainability issues related to their field of research. The graduate reports addressed the material and energy requirements, human factors, sustainability challenges and recommendations for improvement. The assignments and weight contribution of each assignment are presented in Table 3.

Table 3. Assignments and Weight Percentages for the Course Grade

Assignment	**Portion of the Grade**
Attendance and participation	20%
Unit reports	30%
Lab reports	20%
Final project	30%

All course materials, including student assignments, were shared through Microsoft OneNote, a collaborative digital workspace. The purpose of this was to create a content collection of sustainability resources that would be available to the students after the completion of the course. Student unit reports were posted on OneNote, which increased their exposure to other resources. An unintended consequence of using the OneNote collaborative workspace is that it improved the quality of their work. Knowing that the other students would read their reports provided additional motivation to submit their best work in a timely manner.

Pre- and Post-Assessments

At the beginning of the Fall 2023 course, a pre-assessment was given to the students to establish a baseline of knowledge. At the conclusion of the semester, a post-assessment measured student growth in understanding of sustainability concepts. Both assessments were completed by all currently enrolled students: 25 students took the pre-assessment and 27 students took the post-assessment. The results of those assessments are summarized in the following paragraphs.

The 25 students entering the course in Fall 2023 noted qualitatively that they had varying levels of exposure to sustainability.

- Two students were minoring in sustainability
- One student had performed research involving biofuels
- Eight students were exposed to sustainability principles as part of an internship
- Three students were involved with sustainability clubs on campus
- Three students had taken classes focused on sustainability, either completely or in part
- One student received annual sustainability training as part of their K-12 curriculum

Notably, 32% (8 of 25) had sustainability training as part of an internship, while only 12% had courses in sustainability. This shows the emphasis that industry is placing on sustainability efforts and the need to introduce more sustainability in university curriculum. Representative student comments support this conclusion.

> *"No direct sustainability experience, but in my internships its been a big focus when introducing projects: making sure that our improvements aren't negatively impacting our footprint."*
>
> *"[No experience] except through my internship this summer … They keep sustainability as a top priority."*
>
> *"I had a little bit of exposure through courses here at the University of Arkansas. However, most of my knowledge came from my internship this summer."*

Over the course of the semester, students reported growth in both their knowledge and interest in sustainability (see Table 4). While students reported having a moderately strong interest in sustainability at the beginning of the semester (3.76/5), they reported less familiarity with the topic generally (2.80/5) and even less familiarity for applications within the chemical engineering field specifically (2.32/5). At the end of the course, both interest and familiarity had increased and were more balanced.

Table 4. Comparison of Pre- and Post-Assessments, Fall 2023

	Evaluation Score	
	Pre-assessment	Post-assessment
I consider myself passionate about sustainability	3.76	4.07
I am familiar with concepts of sustainability	2.80	4.11
I am familiar with applications of sustainability within the chemical engineering field	2.32	4.11

5 – completely, thoroughly
1 – not at all

Each student was asked to evaluate the impact of each of the course topics. The topics are shown in ranked order in Table 5. In future course offerings, this information could be used to determine which topics need to be improved or eliminated from the course. A general trend is that students reported being more impacted by the topics covered at the beginning of the course. This could be because, as the semester progressed, the content was more than they could absorb. Another explanation could be that the earlier topics were broader and more foundational. For most of the students, this course was their first exposure to sustainability, therefore the foundational concepts impacted them more than the narrower applications.

Table 5. Evaluation Scores for Course Topics, Fall 2023

	Evaluation Score
Three Pillars of Sustainability	4.81
Climate Change and Carbon Footprint	4.70
Greenhouse Gases	4.67
Life Cycle Assessment	4.63
The UN Sustainable Development Goals	4.59
Net Zero Goals	4.59
Plastics and Biodegradable Plastics	4.59
Scope 1-3 Emissions	4.56
Mechanical and Chemical Recycling of Plastics	4.52
Overview of Alternative Energies	4.52
Sustainability, as defined by the Brundtland Report	4.48
Science-Based Targets Initiatives	4.44
Decarbonization Strategies	4.44
Electrification of Transportation	4.41
Waste Minimization	4.37
The 12 Principles of Sustainable Engineering Design	4.15
Corporate ESG Reporting	4.11

5 – enjoyed and contributed to learning
3 – neutral
1 – didn’t enjoy and didn’t learn

In addition to the lecture topics, students assessed the impact of the experiential learning opportunities and lab experiments. These are listed in ranked order in Table 6. The trend that emerges in this list is the importance of active learning. The highest scores were for independent learning activities that focused on the impact of the student's personal choices. These were followed by the labs, the guest speakers (on average), and the polymer pyrolysis demonstration. Due to the long preparation, heat-up and reaction times required for pyrolysis, the students were not able to actively perform the experiment but instead had a passive demonstration. It is also notable that the average score for the experiential learning and labs in Table 6 (4.26) is less than the average score for the lecture content in Table 5 (4.51). Additional work needs to be done to develop experiential learning and labs that the students find both enjoyable and valuable.

Table 6. Evaluation Scores for Experiential Learning and Labs, Fall 2023

	Evaluation Score
Carbon Footprint Calculation	4.70
Zero Waste Challenge	4.59
Trip to Recycling Center	4.44
Solar Panel Efficiency Lab	4.19
H_2 Fuel from Electrolysis Lab	4.07
Guest Speakers (five, averaged)	3.99
Polymer Pyrolysis Demonstration	3.85

5 – enjoyed and contributed to learning
3 – neutral
1 – didn't enjoy and didn't learn

A common theme in the qualitative comments was related to the amount of material. For the most part, students seemed to appreciate the broad exposure to topics related to sustainability within the field of engineering .

> *"I enjoyed the administration of the class. It provided a broad view of various sustainability topics including those I would not instinctively associate with sustainability."*

However, some students felt that the coverage was too broad. They suggested narrowing the topics to allow for sufficient depth of study or for the course to be spread over two semesters.

> *"There are so many elements to sustainability that attempting to cover all of them in such a short period of time means that some elements don't get the amount of coverage that they should."*

When asked about the assignments and class organization, students enjoyed the opportunity to choose the topics for their unit reports (4.52/5). The use of a collaborate digital class notebook through Microsoft OneNote received mixed reviews (4.0/5). Students were split between those who liked having the ability to share resources and explore other student papers and those who found it clunky and complicated. Several students mentioned that, to receive the full benefit of the digital workspace, it should be required to comment on each other's work. Finally, all but one of the 27 students said they would recommend the course to another student.

Conclusions and Future Work

The Introduction to Sustainable Engineering course at the Ralph E. Martin Department of Chemical Engineering at the University of Arkansas has made significant strides in addressing the growing demand for sustainable engineering education. The course has successfully exposed students to a broad spectrum of sustainability topics, encompassing environmental, social and economic aspects.

The course's positive reception, as reflected in student evaluations and feedback, indicates its relevance and impact. Students reported increased interest and familiarity with sustainability concepts, especially within the context of chemical engineering. The incorporation of guest speakers, industry visits and hands-on lab experiments provided valuable experiential learning opportunities, enhancing the overall learning experience.

However, there are areas for improvement and future development:

- Curriculum Refinement: Student feedback suggests that while the broad exposure was appreciated, some felt that the course could benefit from a more focused approach or being spread over multiple semesters. Future course offerings should consider refining the curriculum to strike a balance between breadth and depth.
- Experiential Learning Enhancement: The evaluation scores for experiential learning and labs, though generally positive, indicate room for improvement. Efforts should be made to develop more engaging and impactful experiential learning activities. Incorporating more interactive elements and addressing specific areas of interest expressed by students can enhance the overall effectiveness of these components.
- Quantitative Analysis Integration: Student suggestions for more quantitative analysis in the course curriculum should be considered. Balancing conceptual learning with quantitative analysis could provide a more comprehensive understanding of sustainability principles and their application in engineering.

Building on the success of the Introduction to Sustainable Engineering course, a second sustainability course focused on Life Cycle Assessment (LCA) is under development. Both the Introduction and LCA courses have been provisionally accepted as electives for the University of Arkansas' minor in Sustainability. Increased student interest has also led to the formation of a sustainability-focused student organization in the engineering college. This effort is expected to provide our students with training in the field of engineering sustainability prior to their transition to the workforce. Future follow-up with alumni and employers will be used to mark long-term impacts and opportunities for new content and directions in sustainable engineering education.

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