Chemical Engineering Courses in Sustainability and Life Cycle Assessment

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Abstract

In an effort to provide students with a better background in sustainability and life cycle assessment (LCA) prior to employment, two new undergraduate/graduate elective courses have been added to the Chemical Engineering curriculum at the University of Arkansas. Introduction to Sustainable Process Engineering covers foundational topics in sustainability, including the interconnectedness of the three pillars, energy sources and usage, decarbonization, waste minimization, materials and sustainable design. The course content is tied to real-world applications through industry speakers, site visits, lab experiments and case studies. Environmental Life Cycle Assessment covers LCA methodology for comparative analyses of material and energy systems and processes with the goal of achieving environmental improvements. Impactful topics in the class include the assessment of students' lifestyles and the earth's biocapacity using an ecological footprint calculator, the global impact of plastic waste pollution to the natural environment and biodiversity, and the modeling of styrene-butadiene rubber (SBR) production in openLCA.

Keywords

Sustainability, life cycle assessment (LCA), chemical engineering curriculum, engineering electives

Introduction

In 1987, the United Nations Brundtland Commission [1] defined sustainability as "meeting the needs of the present without compromising the ability of future generations to meet their own needs." While the overall concept of sustainability is easily understood, the approaches used in achieving sustainable solutions differ significantly by discipline. Sustainability in engineering may focus on environmental impact or energy optimization while sustainability in business may focus on Human Resources or supply chain. There can even be differences within engineering disciplines, with chemical engineers focusing on the sustainable design of chemical processes and civil engineers focusing on water treatment or transportation issues. These differences in understanding sustainability by discipline are easily recognized when looking at the requirements for an undergraduate minor in sustainability at the University of Arkansas, (U of A) [2]. While all students pursuing the minor must complete six hours of basic classes in sustainability (SUST 11003 and 21003) and a three-hour capstone project in sustainability (SUST 41003), the remaining nine hours of electives for the sustainability minor may come from courses in 34 different majors.

Engineering has seen a significant increase in the number of academic programs in sustainability over the last two decades. The Association for the Advancement of Sustainability in Higher Education (AASHE) [3] states that there are now 448 engineering programs in sustainability worldwide and 392 in the U.S. alone. Sustainability programs inside engineering also differ by discipline and even inside an engineering discipline. In a 2024 survey of elective courses in chemical engineering, Ford *et al.* [4] found that 45 of the 69 institutions that participated in the survey (65%) offered elective courses in sustainability. Twenty-nine of the 308 "new" courses that were recently created in chemical engineering departments were in sustainability. As is shown in Table 1, sustainable energy was the most popular sustainability elective course topic (22 of the 45 departments or 48% offered a course in this area), although a significant number of offerings were also seen in sustainable design, green engineering and environmental engineering.

Table 1. Sustainability Elective Courses Offered in Chemical Engineering in the U.S. [4]

Course Coverage	% Departments Offering Course*
Sustainable Energy	48
Sustainable Design	32
Green Engineering	31
Environmental Engineering	27
Atmospheric Chemistry	8
Fuel Cell Engineering	8
Pollution Engineering	8
Other	24

*Percentage of departments offering the listed course out of the 45 departments offering courses in sustainability

The purpose of this paper is to introduce two new chemical engineering sustainability courses that are being offered at the University of Arkansas as Tier 1 electives in the popular minor in sustainability. Introduction to Sustainable Process Engineering is a broad-based undergraduate/graduate elective course (for senior and graduate level engineering students) that presents the principles of sustainability across all three pillars—environmental, social, and economic—in a chemical engineering context. Environmental Life Cycle Assessment is a second undergraduate/graduate elective course that covers life-cycle assessment (LCA) methodology for comparative analyses of materials and energy systems with the goal of achieving environmental improvements. These courses help to satisfy the significant student demand for chemical engineering courses in sustainability and the increasing employer demand for our students to have a background in sustainability and LCA prior to employment.

Introduction to Sustainable Process Engineering (CHEG 49203/59203)

Introduction to Sustainable Process Engineering was first offered as a three credit-hour upper-level undergraduate elective and graduate elective course in Fall 2022 and was again offered in Fall 2023 [5]. Student enrollment for the two semesters is shown in Table 2. 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. Pre-assessments given in Fall 2022 and Fall 2023 showed that the students' understanding of sustainability was primarily focused on energy and the environment. Therefore, course topics were chosen to expand the students' views of sustainability into other areas. The Fall 2022 course contained guest speakers and site visits, but it was thought that the students could also benefit from performing lab experiments. Therefore, through funding from a U of A Biggadike Innovation Grant, the Fall 2022 course content was augmented with two lab experiments and a demonstration prior to the Fall 2023 offering.

Table 2. Enrollment in Introduction to Sustainable Process Engineering, Fall 2022 and Fall 2023

Semester	Enrollment	
	Undergraduates	Graduate Students
Fall 2022	20	0
Fall 2023	22	5

Course Content

Table 3 shows the course content from the Fall 2023 semester. The first few weeks covered foundational topics in sustainability, including the interconnectedness of the three pillars. The course provided broad exposure to the field, but the focus was narrowed to areas of impact in process engineering. Topics included energy sources and usage, decarbonization, waste minimization, materials and sustainable design. The course content was tied to real-world applications through industry speakers, site visits, lab experiments and case studies.

Table 3. Course Topics in Introduction to Sustainable Process Engineering, Fall 2023

Weeks	Unit	Topic
1-2	1	Sustainability, as defined by the Brundtland report
		The Three Pillars of Sustainability
		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 and mitigation
		Decarbonization strategies
8-9	4	Developing sustainable materials
		Plastics and 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

Experiential Learning

The Fall 2022 semester course included a carbon footprint study, a zero-waste challenge, and two site visits. In Fall 2023, lab experiments in hydrogen production from water via hydrolysis and solar energy collection using a small solar panel were added to the course, as well as a demonstration of the pyrolysis of waste plastics to fuel. A brief description of each of the experiential learning opportunities is given below.

Each student completed a personal carbon footprint analysis using an online climate calculator, developed by Climate Hero [6]. This led to a class discussion about consumer habits, carbon offsets, carbon taxes and socio-economic considerations. Additionally, students were given an opportunity to voluntarily participate in a zero-waste challenge competition, collecting their generated waste for one week. The waste challenge increased the students' awareness of their waste habits and the impact of lifestyle choices in their waste production. To learn about the materials and economics involved in the recycling process, the class visited the Fayetteville Recycling Facility. Lastly, the class visited a local retail business that is considered a leader in sustainable business practices. The Chief Sustainability Officer shared the systems they have developed to promote and maintain a strong sustainability culture.

In addition to those opportunities, the Fall 2023 semester was augmented with two labs and a demonstration. In the hydrogen production lab, students produced hydrogen from water via electrolysis using a polymer electrolyte membrane (PEM) hydrolyzer. Students performed preliminary calculations on the cost of producing hydrogen from water and compared these to the current U.S. Department of Energy goal for the cost of hydrogen production by electrolysis [7]. This lab experiment led to a class discussion on balancing the environmental and economic pillars of sustainability and highlighted the complexity of switching to alternative energy sources. In the solar energy collection lab, the students used small solar panels to collect energy from an overhead light source, studying the position and pitch. The experiment demonstrated how light is collected with solar panels and subsequently used to generate electricity, while also demonstrating the efficiency of typical collectors. Finally, a laboratory-scale pyrolysis reactor was constructed to demonstrate and study the pyrolysis of waste plastic to produce usable liquid fuel. The design of the pyrolysis reactor was accomplished in consultation with Dr. Willie (Skip) Rochefort, a professor at Oregon State. Due to a 3-hour heat-up time and 3-hour reaction time, it was not feasible for the students to run the entire reaction to completion. Therefore, the pyrolysis reactor was shown as a demonstration to the class, and samples were shown of the source waste plastic and the product oil.

Evaluation

During the Fall 2023 semester, a pre-assessment was given to the students at the start of the semester to establish a baseline of knowledge, and a post-assessment was later given to measure student growth in the understanding of sustainability concepts. Results from these assessments are shown in Table 4. While the 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 with 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

Sustainability Statement	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

The students were also asked to evaluate the impact of each of the course topics. The three pillars of sustainability received the highest score on impact (4.81/5), followed by climate change and carbon footprint (4.7/5), and greenhouse gases (4.67/5). The least favorite topics were the 12 principles of sustainable engineering design (4.15/5) and corporate ESG reporting (4.11/5). Similarly, the students were asked to evaluate the experiential learning activities and rated the carbon footprint calculation (4.7/5) and zero waste challenge (4.59/5) as the best activities and the polymer pyrolysis demonstration as the lowest (3.85/5). Overall, these results showed that students were most impacted by the foundational concepts of sustainability presented at the beginning of the semester. Among the experiential learning activities, the highest scores were for independent learning activities that focused on the impact of the student's personal choices.

Student evaluations through anonymous surveys at the end of the semester contained several qualitative comments regarding the amount of material in the course. 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."*

Environmental Life Cycle Assessment (CHEG 49303/59303)

Environmental Life Cycle Assessment was first offered in Spring 2024 as a three credit-hour upper-level undergraduate elective and graduate elective course to ten undergraduates and six graduate students. The objective of the course was to introduce students to life-cycle assessment (LCA) methodology as a technique to compare process alternatives including materials (biobased vs. petroleum based), energy systems (renewable vs. fossil fuels), consumer products and packaging, and automotive component designs. The challenge is to achieve environmental improvements by developing a hands-on, in-depth understanding of the frameworks, principles, tools and applications of LCA using openLCA software, and to assess the environmental sustainability of products and supply chains. Prior to teaching the class, the instructor attended an on-line training course for openLCA provided by GreenDelta and received training materials for specific topics [8]. The on-line course included private training sessions that covered the basic and intermediate, and part of advanced use of openLCA software. The instructor received post-doctoral training in LCA from Dr. Greg Thoma at the University of Arkansas.

While LCA is an important tool for comparative analysis in industry, it is noteworthy that in the 2024 survey of elective courses in chemical engineering, none of the 45 departments offering sustainability elective courses reported offering a course specifically in Life Cycle Assessment [9]. A review of university websites revealed only a few LCA courses, such as those offered at the University of Michigan and Yale University, indicating that their availability remains limited.

Course Content

Table 4 shows the course outline for the first offering of the class, in Spring 2024. The textbook for the class was *Environmental Life Cycle Assessment* by Jolliet *et al.* [10], which is available as an open access textbook. The most impactful and innovative topics in the class were the calculation of each student's ecological footprint, the contribution of plastics to greenhouse gas emissions and the modeling of styrene-butadiene rubber (SBR) production in openLCA.

The students were very interested in learning about and using an ecological footprint calculator, which is available online [11]. The students assessed the sustainability of their lifestyles and the Earth's biocapacity and seemed surprised to discover how many planets like Earth would be needed if everyone continued to live as they do now. The footprint calculator helped the students understand their impact on greenhouse gas emissions and how they can reduce the impact of their behavior to better protect the environment.

Table 4. Course Topics in Environmental Life Cycle Assessment, Spring 2024

Course Topic	Hours of Coverage
Life cycle assessment (LCA) frameworks, life cycle thinking, methodology, ISO standards	4
Life cycle inventory data sources and quantitative methods	3
Modeling in openLCA with case studies—chicken pasta production, PC vs. PET bottles, polymer production	9
Comparative assessments of projects—diesel car vs. electric car	4

Modeling with parameters and sensitivity analysis	3
Modeling waste treatment management	3
Data quality systems and uncertainty analysis	3
Modeling recycling and product losses	3
Economic input-output LCA	3
LCA for policy and big decisions	2.5

The students were educated on the global issue of plastic waste pollution, which significantly impacts the natural environment and biodiversity. The class emphasized the urgent need to address this trend to mitigate overall climate change, highlighting the reduction of plastic pollution as a critical part of the solution. The discussion inspired students to consider innovative and renewable options that promote environmentally friendly, energy-efficient, and climate-resilient materials.

An LCA software package, openLCA, was used to assess the environmental impacts of synthetic rubber production. The exercise was based on the scenario that an SBR production plant was implementing a corporate social responsibility (CSR) management system, whose goal was to develop a more environmentally friendly product. The students were asked to collect data, conduct an LCA, and write a short report on the necessary steps to create a greener product. Through this exercise, students learned not only how to model with LCA software but also that the software "only provides numbers." Engineers must analyze the results, extract relevant information, and use it to prepare a meaningful message.

Case Studies

Several case studies were utilized in the course including the environmental impact assessment associated with the production of 1 kg of chicken pasta, modeling polycarbonate (PC) and polyethylene terephthalate (PET) bottles in openLCA, modeling SBR production in openLCA, modeling lithium-ion batteries in electric cars, and a comparative assessments of diesel cars versus electric cars.

Most of these case studies were sourced from GreenDelta training courses or are publicly available online. The LCA case study on chicken pasta production was found through a YouTube video [12]. The tutorials for modeling PC and PET bottles, as well as SBR production, are available on the openLCA website [13]. The modeling of lithium-ion batteries in electric cars and a comparative assessment of diesel cars versus electric cars were found from openLCA software training courses [8].

These case studies covered various sectors of industry, including agriculture, energy systems, transportation, and chemical processing. This diversity allowed students to gain experience with different databases and modeling methods. The students showed great interest in all the case studies, which demonstrates that the use of case studies is an effective way to get students to practically apply their understanding of LCA analysis to real-world scenarios.

Evaluation

Students enjoyed analyzing and interpreting LCA results from case studies such as chicken pasta production and SBR production, as these allowed them to draw conclusions about the environmental performance of various products and processes. Analyzing environmental impacts of real-world products and processes helped students understand the practical relevance of LCA. The case study that had the most significant impact on their learning was the comparative assessment of diesel cars versus electric cars. Through the detailed examination of the topic, students gained insight into strategies for designing and modeling products to mitigate environmental impacts, including the use of sustainable materials and processes. The course was well received by the students, as evidenced by the following comments.

> *"I am beyond happy that I chose this chemical engineering elective. Not only was it taught by a very helpful and knowledgeable professor, but it was so much fun to be able to learn something that I know will be helpful in my future career since Dr. Kim showed us the various applications our skills can be applied to. I will continue to recommend Dr. Kim's classes to other students as they are truly so beneficial to our learning."*

> *"The class was helpful because it connected how chemical engineers might use software and databases to determine the environmental impact a process could have. A main focus of the course was learning the software openLCA, but the introduction to sustainability gave me some basic comprehension over impact categories and units, the components of a full life cycle assessment, and the theory to develop each of the components. Although I do not want to pursue a career in sustainability, the course taught the necessary details to be well informed in future sustainability talks and discussions."*

The first comment was provided anonymously on the course evaluation. The second comment was in response to a call for student comments after the conclusion of the semester.

Conclusions and Future Work

In adding elective courses in sustainable process engineering and environmental life cycle assessment, the Ralph E. Martin Department of Chemical Engineering at the University of Arkansas has taken a big step in preparing their students for employment opportunities which require a sustainability or LCA background. Student interest in the classes is quite high and the incorporation of guest speakers, industry visits, hands-on lab experiments and hands-on LCA training with application enhances the overall learning experience. By continuing to solicit student input on course content, both of the courses will soon be providing students with good backgrounds on sustainable chemical engineering practice. Areas for improvement and future development of these courses include:

- Curriculum Refinement. Student feedback suggests that while the broad exposure in the sustainable process engineering course was appreciated, some felt that the course could benefit from a more focused approach. Future offerings of this course should consider refining the curriculum to strike a balance between breadth and depth.
- Experiential Learning Enhancement. Efforts should be made to develop additional and more engaging and impactful experiential learning activities in both courses.

Incorporating more interactive elements and addressing specific areas of interest expressed by students can enhance the overall effectiveness of these components. Additional lab experiments could be developed for the Sustainable Process Engineering class and are ideal places for the addition of an LCA study of the experiments.
- Student Assessment. Ongoing assessment of the students would provide valuable insights into the effectiveness of the courses and identify areas of improvement. The course instructors will continue to solicit student comments on the content of the courses and delivery methods to help guide future offerings and refinement of the classes, ensuring they remain relevant and effective in meeting educational objectives.

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