Integrating Sustainability into a Core Chemical Process Safety Course

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Abstract

The modern chemical engineering curriculum must evolve to address the global imperative for sustainable design and practice. While dedicated elective courses on sustainability are valuable, integrating these concepts into core, required courses are essential to demonstrate their fundamental importance. This paper details a novel, student-led initiative to infuse sustainability principles into a mandatory undergraduate chemical process safety course. By linking sustainability to the industrially-relevant and federally-mandated topic of process safety, we underscore its critical role in responsible engineering.

Our approach is to have senior-level undergraduate students, who have completed courses in both process safety and sustainable engineering, serve as the primary content creators. Under faculty guidance on pedagogy and accreditation requirements, these students develop transferable course modules designed to resonate with their peers. This "student-as-creator" model aims to filter content through the lens of what students find most engaging and relevant, shifting the dynamic from passive learning to active co-creation of the curriculum.

The developed modules bridge the gap between process safety and sustainability through a series of lectures, case studies, and assignments. Key topics include the UN Sustainable Development Goals, the twelve principles of green chemistry and sustainable engineering, and life-cycle assessment. These foundational concepts applied to broader themes such as materials selection, systems thinking, and corporate social responsibility.

This initiative will hopefully serve as a replicable model for empowering students in curriculum development, ensuring that educational content remains dynamic and relevant. By embedding sustainability within the core framework of process safety, we aim to cultivate a new generation of engineers who instinctively recognize that a safe process is inherently a sustainable one.

Introduction

The chemical engineering profession is facing a change in thinking. As the United Nations' 2030 Sustainable Development Goals (SDGs) emphasize the urgent need for responsible consumption and production, chemical engineers are increasingly tasked with designing processes that balance technical performance with environmental and social impacts. This global imperative is reflected in the accreditation standards for engineering programs. ABET Student Outcome #2 explicitly requires that engineering design solutions be produced with consideration for "public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors" [1].

Despite this mandate, sustainability is frequently treated as an isolated topic in the undergraduate curriculum. It is often relegated to elective courses or minor modules, rather than being integrated into the core sequence where students encounter the fundamental constraints of engineering practice. This segregation risks signaling to students that sustainability is an external constraint or a specialization, rather than a central tenet of modern chemical engineering design [2]. To cultivate a generation of engineers who instinctively recognize that a safe process is inherently a sustainable one, we must embed these concepts into the core, mandatory coursework [3].

Chemical Process Safety offers a unique and powerful vessel for this integration. The discipline has already evolved from a focus on unit operations to a holistic systems approach, prioritizing safe design, operation, and management. The emerging concept of "Safe and Sustainable by Design" (SSbD) highlights the natural intersection between these fields; both safety and sustainability require systems thinking, life-cycle analysis, and the ethical management of risk [4].

However, effectively integrating these complex themes requires innovative pedagogy that moves beyond passive instruction. This paper presents a novel initiative utilizing a "Students as Partners" (SaP) model to bridge the gap between safety and sustainability [5]. The SaP approach repositions students from passive consumers of knowledge to active collaborators in curriculum development, a method shown to increase student engagement, ownership, and confidence [6].

In this initiative, senior-level undergraduate students who have previously completed coursework in both the process safety and sustainable engineering courses served as primary content creators. Under faculty guidance, these student-partners developed transferable course modules linking the twelve principles of green chemistry and Life Cycle Assessment (LCA) directly to process safety fundamentals. This paper details the structure of this student-led curriculum development, the specific modules created, and the framework for implementing this "student-as-creator" model in a standard chemical engineering program.

Background

While the integration of sustainability into chemical engineering curricula is increasing, the methods of implementation vary significantly across institutions. A common approach has been the addition of specialized electives or a "whole curriculum" rebranding. For instance, the University of Rochester [7] recently renamed its department to "Chemical and Sustainability Engineering," reflecting a research and elective-heavy focus on sustainable energy and remediation. Similarly, James Cook University [8] in Australia has embedded sustainability into approximately 30% of their degree program, utilizing fourth-year design projects as the primary vessel for assessing sustainable decision-making.

Recognizing that electives may not reach all students, other universities have moved toward a "bottom-up" infusion of sustainability into required core courses. The University of Wisconsin-Madison [9], as part of the "Engineering for One Planet" (EOP) framework, recently launched a pilot to recruit instructors of mandatory engineering courses to embed relevant sustainability lessons, moving away from the "one standalone class" model. Kettering University adopted a similar modular approach by redesigning their *Industrial Organic Chemistry* course to teach traditional reaction mechanisms through the lens of the 12 Principles of Green Chemistry [10].

Specific precedents for combining process safety with sustainability also exist, though they often focus on environmental compliance rather than holistic sustainable design. The University of Edinburgh [11], for example, offers a combined course titled *Process Safety and Environmental Issues*, which links risk assessment (HAZOP, fault trees) directly with pollution mitigation and environmental regulation.

However, a gap remains in utilizing "Students as Partners" to generate this content. While institutions like Villanova University have utilized top-down "Sustainability Leadership Councils" to drive curriculum change, our approach creates a unique opportunity for students to co-create the bridge between the rigid, federally mandated world of Process Safety (OSHA/PSM) and the broader, ethical mandate of the UN Sustainable Development Goals [12].

Methodology

This initiative targets *Chemical Process Safety*, a required core course taught in both the Fall and Spring semesters. The impetus for this curriculum redesign stems directly from student feedback. Senior exit interviews conducted over the past three years have consistently detailed a student desire for sustainability concepts to be integrated explicitly into required coursework, rather than remaining isolated in electives. Responding to this demand, the instructors initiated a project to infuse sustainability into the safety curriculum, leveraging the federally mandated and industrially relevant framework of safety (via OSHA and NFPA) to demonstrate the necessity of sustainability knowledge in the modern workforce. It should be noted that the combination of sustainability and safety is not a traditional union of engineering concepts, which is why the authors have contributed this work. Previous efforts at the university have added concepts of sustainability to senior-level process design and capstone courses as well as first-year introductory courses and labs. These efforts contributed to the formation of a bachelor's degree emphasis on Environment and Sustainability. This work focuses on the core safety course.

To ensure the curriculum resonates with the student body, we adopted a "Students as Partners" approach. Funding was secured to hire undergraduate student researchers to collaborate with faculty in generating course content. The selection criteria for these student partners were strict: candidates must be "rising seniors" who have successfully completed both the required (core) safety course and the elective *Sustainable Engineering* course. This small group of students were more likely to find gaps in what material was not being covered in the safety course as well as inform instructors of foundational material that all students would benefit from that were discussed in the elective course.

This prerequisite ensures that the student partners possess the necessary technical foundation to bridge the two disciplines. While faculty provide guidance on pedagogy and accreditation requirements, the students drive the primary content creation. This structure aims to filter the curriculum through a "student perspective," mitigating potential faculty bias and ensuring the material addresses what students genuinely want and need to learn.

The development process begins with a literature review of current practices at peer institutions, guided by the faculty. Following this, student partners help create transferable content modules designed to be "packaged" and taught by potentially revolving faculty, ensuring the longevity of the initiative.

The content is divided into distinct and general topics to provide a comprehensive overview of the safety-sustainability nexus:

- Distinct Foundational Topics: (1) The UN Sustainable Development Goals (SDGs) and the history of sustainability; (2) The 12 Principles of Green Chemistry; (3) The 12 Principles of Sustainable Engineering; and (4) Life-Cycle Assessment (LCA).

- General Applied Topics: (5) Materials selection; (6) Social responsibility; (7) Responsible business and economy; and (8) Systems thinking.

These topics are delivered through various pedagogical methods, including traditional lectures, active discussions, assignments, and case studies that highlight the dependency of process safety on sustainable practice. Foundational topics had dedicated days in the semester to go over the content and to introduce new concepts, e.g., life cycle assessment. Other (general) topics that overlap with sustainability complemented design and safety considerations. These were largely informed by the Engineering for One Planet (EOP) Framework, its learning outcomes, and associated publications. Authors of this manuscript have contributed to some of these EOP resources.

Most content was delivered via classroom interaction, but some supplemental or expansive resources were made available outside class via the university's learning management system, Canvas. Sustainability-focused content was mixed with other content throughout the semester, but dedicated days were placed at the beginning of the semester and at the beginning of new content, e.g., after exams. Overall, approximately three weeks of concepts of sustainability were added to the course, removing minor safety concepts and advanced modeling techniques. While these safety topics are certainly important, instructors prioritized content that would benefit students from a holistic point of view.

Assessment Methodology

To evaluate the efficacy of the student-generated modules, we employed a direct assessment method focused on student competency in applying sustainability principles to real-world safety scenarios. The primary instrument for this assessment was a case study on Bhopal, a summative assignment requiring students to analyze the 1984 disaster through the specific lens of the 12 Principles of Sustainable Engineering.

Student mastery was measured using a criterion-referenced rubric designed to assess high-level cognitive skills (synthesis and evaluation) rather than simple recall. The rubric was weighted to prioritize critical thinking, with 90% of the grade derived from three core competencies:

- Identification of Principles (30%): The ability to clearly identify relevant sustainability principles (e.g., "Inherent Rather Than Circumstantial" or "Prevention Instead of Treatment") as they relate to specific technical failures.
- Holistic Understanding (30%): The capacity to demonstrate how these principles offer a broader perspective on the tragedy, moving beyond immediate mechanical failures (such as the VGS saturation) to systemic issues.
- Application to Mitigation (30%): The ability to convincingly explain how designing with these principles could have served as an inherent safety layer to mitigate or prevent the incident.

Data was collected over two semesters: Spring 2025 (N=31) and Fall 2025 (N=14). The assessment specifically tracked the students' ability to transition from viewing safety as a compliance exercise (OSHA/PSM) to viewing it as a component of sustainable design.

Results and Discussion

To assess the efficacy of the student-generated curriculum, a pilot module was deployed in the Chemical Process Safety course during the Spring 2025 and Fall 2025 semesters. The module culminated in a case study about the Bhopal, India Union Carbide disaster which tasked students with re-evaluating the 1984 tragedy through the lens of the 12 Principles of Sustainable Engineering.

Students were provided with technical data [13-15] regarding the failure of the MIC refrigeration system, the decision to use carbon steel piping, and the saturation of the Vent Gas Scrubber. Using a rubric focused on "Holistic Understanding" and "Application to Mitigation Strategies," students were required to demonstrate how sustainable design could have served as an inherent safety layer.

Analysis of student performance data indicates a high level of mastery of the integrated concepts.

<u>Spring 2025 (Initial Pilot):</u> The class (N=31) achieved a submission rate of 84%. Among students who submitted the assignment (n=26), the average score was **88.8%**. Notably, 58% of the submitting students achieved a perfect score of 100/100, demonstrating "excellent" identification of sustainability principles and their application to mitigation strategies[4]. This was a new case study for the course; no previous baseline was established.

<u>Fall 2025 (Refined Iteration):</u> The subsequent cohort (N=14) showed improved performance. With a submission rate of 93% (n=13), the average score rose to **98.5%**. Every submitted assignment scored 90% or higher, with 77% of students achieving a perfect score.

These results suggest that the "student-created" nature of the content filtered complex sustainability principles through peer-accessible language by successfully bridging the gap for learners. The drastic reduction in lower-tier scores (those that received below 80%) between Spring and Fall may also reflect the refinement of the module delivery by the student partners. The influence of year-to-year passing of assignments or the use artificial intelligence (large language models, LLMs) was not investigated in the current study.

The qualitative success of the module is best illustrated by the connections students drew between specific process safety failures and sustainability principles. By moving beyond standard Root Cause Analysis (RCA), students identified that "safe" designs are often synonymous with "sustainable" ones. Common student insights included:

- Principle 1: Inherent Rather Than Circumstantial: Students frequently cited the storage of twenty-eight tons of MIC as a violation of this principle. They noted that an inherently safer/sustainable design would have minimized inventory (using "generation-on-demand"), thereby eliminating the hazard source rather than relying on "circumstantial" add-ons like the refrigeration unit which had been turned off to save costs.
- Principle 2: Prevention Instead of Treatment: Students criticized the reliance on the Vent Gas Scrubber (VGS) and Flare Tower. They correctly identified these as "end-of-pipe" treatments. When the runaway reaction released 40 psig of gas, these treatment systems were overwhelmed. Students argued that a sustainable approach would focus on preventing the waste generation (the runaway reaction) rather than treating the emission.

- Principle 7: Durability vs. Immortality: The decision to downgrade piping metallurgy from stainless steel to carbon steel was identified as a failure of durability. Students noted that while "Value Engineering" saved initial capital, it created a non-durable system prone to corrosion and clogging (MIC-Trimer formation), which compromised the safety integrity of the plant.
- Principle 6: Conserve Complexity: Students highlighted the "workaround solutions" and jumper lines used at the plant as violations of simplicity. They argued that the complexity added by these temporary fixes obscured the system's true state, contributing to the "normalization of deviance".

By framing the Bhopal tragedy through these principles, students demonstrated a holistic understanding that satisfied the "Excellence" criteria of the rubric: they effectively argued that designing for sustainability is not merely an environmental exercise, but a fundamental strategy for catastrophic risk reduction.

Informal reflections from the student partners show that the content creation process required them to connect sustainability principles to real engineering applications and decisions rather than treating them as abstract concepts. In deciding instructional topics, student partners evaluated how sustainability considerations influence design choices, risk reduction, and operational decisions. This engagement deepened their understanding of sustainability as engineering practice and not only as theoretical concepts. This suggests the student partners model created meaningful learning not only for their peers but the student partner themselves.

Conclusion

The modern chemical engineering curriculum must evolve to meet the dual challenges of operational safety and global sustainability. This paper outlines a successful framework for addressing this need by integrating sustainability concepts directly into a mandatory Chemical Process Safety course. By eschewing the traditional model of isolated elective courses, we demonstrated that sustainability is not a peripheral concern but a core tenet of responsible engineering practice.

Central to the success of this initiative was the "Students as Partners" model. By empowering senior-level students to co-create the curriculum, the resulting content was inherently designed to resonate with the student body, specifically the Bhopal and Green Engineering modules. The assessment results, showing a high rate of mastery and engagement across two semesters, validate the hypothesis that students are eager to explore the intersection of these disciplines.

This initiative highlights that a safe process is inherently a sustainable one. Through the lens of the 12 Principles of Sustainable Engineering, students were able to re-evaluate historical safety failures not just as mechanical breakdowns, but as failures of sustainable design. This work serves as a scalable model for other institutions seeking to infuse sustainability into the core curriculum, ensuring that the next generation of engineers enter the workforce equipped to solve the complex, interconnected problems of the future.

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